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WRIGHT LABORATORY

# LASER PAINT STRIPPING

J.D. Head, J. Peter Niedzielski
Laser Technologies, Inc.
10131 Colonial Industrial Drive
South Lyon, Michigan 48178



June 1991

Final Report for Period April 1988 - January 1991

Approved for public release; distribution unlimited.



WRIGHT LABORATORY
MATERIALS DIRECTORATE
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433-6533

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Gary D. Meuer

GARY D. MEUER, Captain USAF
Materials Behavior & Evaluation Group
Materials Engineering Branch
Systems Support Division

Theodore J. Reinhart

THEODORE J. REINHART, Chief
Materials Engineering Branch
Systems Support Division

FOR THE COMMANDER

Thomas D. Cooper

THOMAS D. COOPER, Chief
Systems Support Division
Materials Directorate

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A study to assess the utility of high powered CO2 pulsed laser depainting methods was conducted on aluminum and graphite epoxy composites. The various tests were designed to detect potential forms of damage or loss of properties of various aircraft structural materials during removal of paint with pulsed laser energy. Tests for changes in physical properties, paint adhesion and corrosion protection of repainted materials showed no detectable adverse changes in any of the samples studied.

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## EXECUTIVE SUMMARY

A Phase II Small Business Innovation Research (SBIR) program to study the use of pulsed carbon dioxide(CO2) lasers for depainting was conducted by Laser Technologies, Inc. This investigation was preceeded by a laser phenomonology study under a Phase I SBIR which demonstrated controllable paint removal without evident substratum damage on a variety of paint and substratum combinations using a high peak power short pulse laser.

Work on this program was divided into two phases. The first phase involved range finding investigations of surface effects caused by laser depainting including adhesion, corrosion resistance, surface roughness, temperature rise, and acoustic shock effects.

The second phase involved more quantitative examination of these properties as well as additional subject areas including laser related electromagnetic pulse effects on electronic components, noise determinations, surface morphology, surface cleanliness, laser fluence variations, and material property effects on both aluminum and composite structures.

The application of the technology to a number of typical cleaning problems was also examined. Waste collection and beam delivery problems were also studied in sufficient detail to insure that a practical system could be readily built.

Adhesion tests provide conclusive evidence that in-so-far as adhesion is concerned, laser depainting causes no negative effects and may enhance adhesion.

On corrosion and humidity tests the laser depainted samples showed significantly fewer failures than control samples. The use of standard cleaning procedures after laser depainting and prior to repainting resulted in an increase in corrosion failures as compared with directly repainted samples. The study suggests that materials should be painted directly after laser depainting with no intermediate washing or other cleanup procedures.

Surface roughness in all cases appeared to be decreased by painting and subsequent laser removal of the paint. The laser depainting retains the smoothness of the original paint film and leaves the holes filled.

Significant damage to anodizing occurs during pulsed laser paint removal using pulse durations of less than 2 microseconds. At pulse duration of 25 microseconds and energy density of 5-25 Joules per sq cm per pulse no damage to sulfuric acid anodizing of Aluminum alloy 2024 bare anodized or Aluminum alloy 7075 bare anodized could be detected.

Studies of the off gas stream shows that solids equal to the pigment content of the coating being removed are collectable. These solids have only traces of organic material indicating that

the organic content of the paint film is largely converted to carbon dioxide and water.

The laser cleaning produces instantaneous combustion of the waste products and thus not only removes paint but also disposes of the removed paint by combustion. The determination of possible requirements for control of the waste stream awaits such measurements as will be available only from a fully operational system.

With high pulse rate (100/sec) equipment the heat build up on the reverse side of a 0.032 anodized aluminum sample did not exceed 150 degrees F with 500 pulses of 5 J/sqcm. The heat build up in less thermally conductive graphite-epoxy composite materials is significantly greater than in the case of aluminum. However, maximum temperatures at the base of the first ply of a composite sample during total removal of paint did not exceed the recommended temperatures for the heat baking step of the original paint application.

In practical applications the energy applied to a painted surface is largely adsorbed and utilized in paint decomposition resulting in very small temperature rise in the substratum. Once the paint film is largely removed a greater portion of the energy is directed to the substratum and the reflectivity, conductivity and mass of the substratum determine the temperature rise.

No detectable shock wave was transmitted through laser depainted samples. Similarly, no EMP effects could be detected from any of the lasers used in these studies. Noise levels with use of a rapid pulse high energy laser do not exceed 90 decibels at 2-3 ft from the work surface.

With the lack of detectable effects by other methodologies, only a few special samples were examined in photomicrographs. Even in such cases no evidence of damage could be found.

Complex shapes presented no problems which could not be solved by manual manipulation of the laser delivery head. Turbine blades, fastener heads and composite structures were successfully cleaned and/or depainted.

Effective paint removal rates are obtained with fluence of greater than 6 J/sqcm per pulse. Below that level there is increasing evidence of soot formation and charring. At beam intensities of less than 3 J/sqcm serious paint charring occurs and might increase the risk of leaving residual carbon. At increased fluence above 6 J/sqcm there is improved removal efficiency as measured by paint removed per Joule of energy supplied. It appears that optimum fluence range is 8-12 J/sqcm.

There was no evidence of change of tensile properties after four cycles of laser depainting and repainting aircraft aluminum nor evidence of change in crack growth rates of 0.016 inches thick aluminum alloy sheet, 2024-T3 bare, after four cycles of laser

depainting and repainting.

The standard Almen shot peening intensity tests gave no observable deformation. A redesigned test to give the greater sensitivity of single point mounting and longer free arm to increase level of detectable bending failed to disclose any deformation during laser depainting. As expected the laser interaction produces no discernable compressive forces on the surface being depainted.

Tensile tests showed a possible small decrease in tensile strength of 16 ply unidirectional IM6/3501-6 Graphite/epoxy composite after four cycles of laser depainting. The data scatter for the laser depainted samples was narrower than for the control samples and all measurements were within the expected scatter range for this type of material when measured in the matrix dominated direction. The tests perpendicular to fiber direction in the unidirectional composite were selected as most sensitive indicators of damage.

Flexural tests on the graphite/epoxy composite showed an increase in strength of the five samples tested. It is possible that the residual paint contributed to improved test results through surface modification. Compression tests also showed an increase in strength of the five samples tested. Both tests indicate that laser depainting did no damage.

Previous depainting studies with lasers had resulted in the fear that a carbon residue may be left on the work piece and might cause future corrosion. In this investigation all possible carbon formation situations were observed and attempts were made to collect and analyze any suspect material. Chemical analytical methods showed no evidence of residual carbon.

Indirect testing for the presence of carbon through corrosion testing of seamed samples showed no evidence of carbon induced corrosion. Carbon and soot like residues are produced with low fluence laser energy. All of the depainting done for this study was conducted in the more practical operating range of at least 8-10 joules per sqcm. At such fluence, a clean reaction occurs with no evidence of carbon deposits, even in cracks.

A complete environmentally sound, economic system for the cleaning of aircraft was designed based upon the data derived during this study.

The results of this extensive study of the effects of the pulsed laser system on aircraft materials has successfully opened the potential for many applications of pulsed laser cleaning within the aircraft and aerospace markets as well as other totally unrelated markets. The validation of the benign nature of the process obtained through this study has enabled other industry segments to look at pulsed lasers as a truly viable new solution to very old and persistent problems, such as lead based paint removal, containment and disposal.

## FOREWARD

Laser Technologies, Inc. and the associated organization Laser Technology, Inc. have had many years of corporate commitment to the development of pulsed lasers for the removal of paint and other surface treatment applications. This commitment has included the development of high powered pulsed lasers and studies of their application. The subject contract is a part of this overall effort with specific attention to the examination of the effects, if any, of pulsed laser paint removal on the properties of aircraft structural materials.

Data included in this report reflect the progress of the contractor in the development of industrial laser paint stripping systems.

The data reported herein represent the results of studies of the effect of laser cleaning on aircraft materials. This project has been sponsored by:

Wright Laboratory
Materials Directorate
Aeronautical Systems Division (AFSC)
United States Air Force
Wright Patterson Air Force Base, Ohio 45433-6533

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# 1.0 OVERVIEW

## 1.1 Introduction

The purpose of this work is to quantitatively define and determine the material effects of pulsed carbon dioxide ($CO_2$) laser depainting as applied to typical Air Force materials. Samples of airframe materials, including aluminum and graphite fiber composites, were subjected to repeated painting and laser cleaning cycles, with testing to determine the effects, if any, of such repeated exposure to laser energy on all significant properties of the materials. A sufficient number of samples were tested to provide statistically significant data to support application of the methodology. Turbine blade samples were also cleaned and returned to suppliers for evaluation. In addition characterization of off-gas products were included to develop data for design of an off-gas collection and handling system. Preliminary studies of the control problems associated with application of this technology to aircraft are included.

## 1.2 Paint Stripping Background

### 1.2.1 Aircraft Substratum

Aluminum sheet metal "skins" have been the predominant form of aircraft material subject to paint removal for many years. Various forms of aluminum both with and without anodizing corrosion protection are in current use. More recently, organic matrix composites have become sufficiently developed to find wide application in selected sections of both military and commercial aircraft.

The studies conducted under this contract considered both aluminum and composite substratum. Materials selected for testing include 2024-T3 and 7075-T6 aluminum alloy representing typical aircraft fusilage and wing skin material and IM6/3501 prepreg graphite epoxy composite material representing typical advanced composite skin material.

### 1.2.2 Current Paint Stripping Processes

Paint coatings are used to perform a variety of functions on all aircraft systems including protection against corrosion, camouflage, thermal protection, and erosion resistance. During the life of the systems, the coatings require removal for a variety of reasons from replacement of the worn coatings to changes in camouflage schemes. Removal of the chemically resistant coatings used on weapons systems has involved chemical strippers. As an alternate process to chemical paint stripping, mechanical paint removal by abrasive blasting using various abrasive media has also been studied.

The chemical stripper methods of paint removal are labor intensive and require the use of strongly activated chemical

strippers. Improvements in coating materials, particularly the more recently introduced epoxy and polyurethane coatings, introduced greater resistance to chemical removal systems and further complicated the removal problems. Mechanical assists to the activated chemical agents increased the labor intensivity of the operation. The activating agents introduced pollution, work place hazard, and environmental problems.

The chemical stripper methods become difficult to use on aircraft structures made up of organic matrix composites, such as graphite/epoxy. Such structures are similar in chemical composition to the coatings being used and removed. The chemical systems which will remove the coatings will also attack the substratum and are difficult to control as to such attack.

An alternative process for removal of paint involving only mechanical energy applied by abrasive blasting has been extensively studied. Abrasive media which have been evaluated include crushed corn cobs, glass beads, walnut shells, synthetic diamond dust, garnet, dry ice pellets, plastic pellets and high pressure water. All such methods have shown limited success due primarily to the tendency of all such systems to transmit energy into the substratum causing adverse changes in physical properties. Plastic media blasting has been widely implemented for depainting aluminum surfaces and has been authorized for use on composites in the Air Force. However, continuing concern persists over blast induced damage to thin and delicate structures.

## 1.3 Laser Paint Stripping

The use of laser energy to remove and destroy the surface material has been considered by several investigators but all such programs have run into the difficult problem of control of the laser energy so as to avoid damage to the substratum. The potential for economic laser removal of paint has been enhanced with the development by Laser Technologies, Inc (LTI) of a high-power, short-pulsed, $CO_2$ laser that possesses homogeneous beam characteristics. LTI has conducted experiments that verify the ability of this laser system to remove paint from metals, including aluminum, and from carbon fiber reinforced composites cleanly and without damage to the underlying surface.

Prior work done for the Air Force established the existance of an operating window of energy concentration between low levels of energy per pulse which promotes charring or burning of the paint and high levels of energy per pulse which might induce substratum damage. This previous work was limited by the flexibility of the lasers used in the tests and the range of satisfactory operation was not fully explored.

## 1.4 Laser Technologies, Inc. Systems.

Laser Technologies, Inc. and Laser Technology, Inc. have invested

in the study and development of several approaches to the production of high powered rapid pulsed $CO_2$ lasers. This work which is not part of the subject contract supported the use of a variety of pulsed laser equipment to supply variations in pulse duration and pulse frequency as well as pulse energy density in the work reported herein.

### 1.4.1 High Power Single Pulse Equipment

Preliminary tests were carried out utilizing a high peak power laboratory $CO_2$ laser, located at Plasmatronics, Inc. in Albuquerque, NM. This equipment produced pulses of 30-50 joules, of 0.3-2.0 microseconds duration giving a large footprint. The equipment, however, produced such pulses at only 10 second intervals. Much of the initial phenomonology study was accomplished using this laser. Useful data as to fluence requirements for paint removal and other range finding results were obtained.

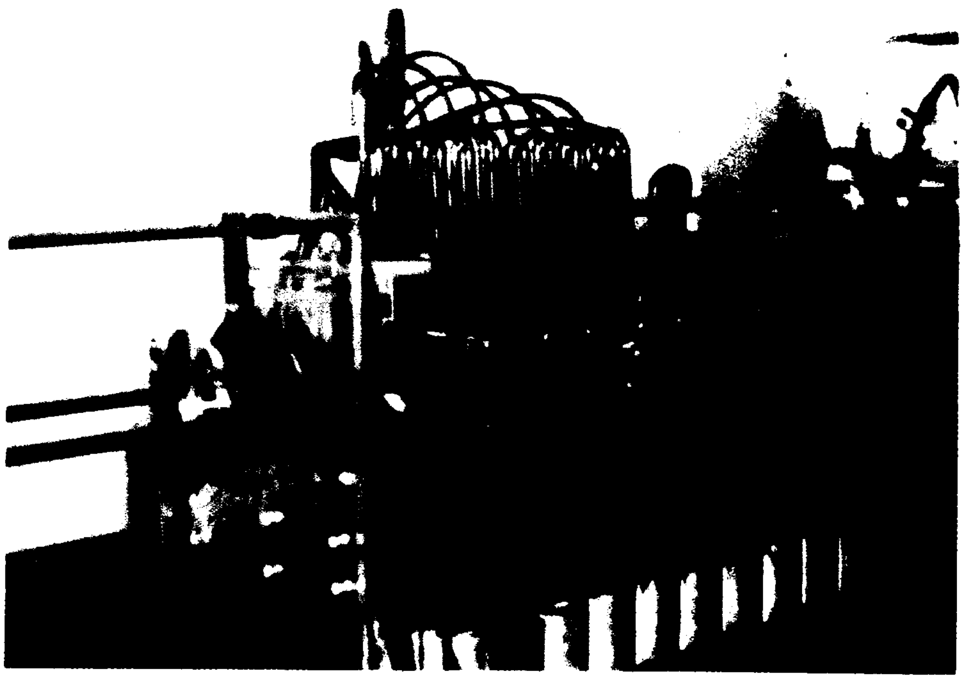


**Figure 1. Single Pulse Equipment**

### 1.4.2 Low Power Rapid Pulse Equipment

Extensive use was made of a 10 watt pulsed laser with output of 1.2 joules per pulse at a rate of 8 pulses per second. The pulse duration was 25 microseconds. This equipment was located in the Laser Technologies, Inc. facilities. The beam was passed through a 4 inch focal length lens and samples were exposed in the region beyond focus. Samples were mounted on an x-y table so that manual movement of the samples past a stationary laser beam could provide for scanning of samples and consequently uniform exposure of a full sample to the depainting action of the laser. Variation of fluence was accomplished by setting the x-y table at varying distances from the focal point of the divergent beam and fluence could be varied from 1-25 joules per square centimeter per pulse. Waste product was removed through a simple vacuum system.

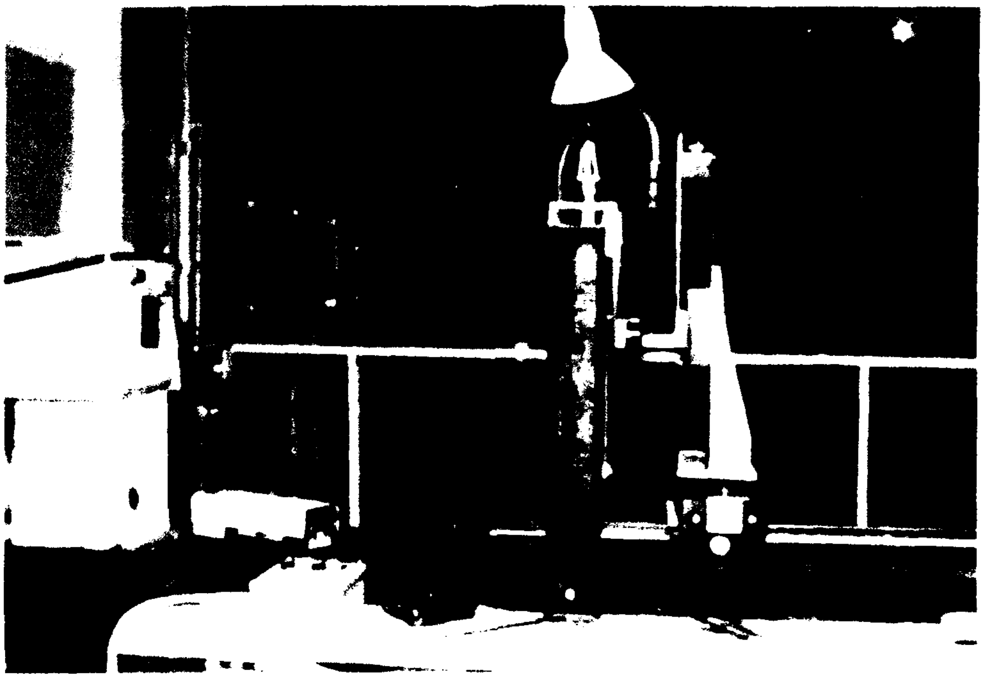


**Figure 2. Low Power Rapid Pulse Equipment**

### 1.4.3 High Power Rapid Pulse Equipment

Larger paint removal areas were achieved with the full scale LTI equipment which produces an output of 1.2 joules per pulse at a variable rate from 40-250 pulses per second. This equipment can produce pulses of controlled duration varying from 10 to 30 microseconds. The pulse characteristics are very nearly identical to those produced by the lower powered equipment described under 1.4.2. The same x-y table and lens system allowed similar control of uniformity of treatment and variations of fluence.

The simple vacuum system was satisfactory for removal of waste products. The equipment was also used for the development of the wobbler system for automatic distribution of the pulses along a line which was manually advanced across a sample by the use of the x-y table. The wobbler was equipped with a 10 inch focal length reflector and samples exposed beyond focus were given exposures of 8-20 J/sqcm according to the distance from focus.

**Figure 3. High Power Rapid Pulse Equipment**

## 1.5 Work Locations

### 1.5.1 Laser Technologies, Inc.

All tests and results not specifically designated as being performed elsewhere, were carried out in the contractors facilities located at 10131 Colonial Industrial Drive, South Lyon, Michigan.

### 1.5.2 Detroit Testing Laboratories

7111 East Eleven Mile
Warren, Michigan 48092

An independent testing and metallurgical laboratory Detroit Testing Laboratories was founded in 1903. They are specialists in materials testing. Testing is conducted in accordance with ASTM, ANSI, Ul, Military, Federal, automotive, and other industrial specifications and standards.

This laboratory conducted all mechanical tests except fatigue crack growth..

### 1.5.3 PRA Laboratories Incorporated

430 West Forest Avenue
Ypsilanti, MI 48197

A testing laboratory conducted in association with the Coatings Research Center of Eastern Michigan University, Ypsilanti, Michigan; Director - Dr. John Graham.

This laboratory conducted salt spray and humidity chamber corrosion tests.

### 1.5.4 Battelle Research Institute

505 King Avenue
Columbus, Ohio 43201

An internationally recognized metallurgical research and testing institution.

This laboratory conducted fatigue crack growth tests.

## 2.0 TESTS PERFORMED

### 2.1 Phase II A Work

The test program was divided into two Phases. The Phase A work included range finding tests and exploration of a variety of potential sources of damage in order to select those most appropriate for more detailed study in phase B.

#### 2.1.1 Paint Adhesion

Wet adhesion tape tests were conducted to identify the presence of adhesion problems, if any, caused by laser cleaning. Such tests also defined the requirements for further washing or other cleaning of materials prior to repainting.

#### 2.1.2 Corrosion Resistance of Painted Panels

Humidity and salt spray corrosion tests were made to confirm the ultimate useful integrity of cladding and /or anodized surfaces after laser depainting.

#### 2.1.3 Surface roughness.

The Small Business Innovative Research (SBIR) Phase I work gave no indication of change in surface roughness caused by laser depainting However, in view of changes in surface roughness encountered with alternate depainting methodologies, measurement of this property is essential to confirm that laser depainting will create no problems of this nature such as are created by alternate cleaning technologies.

#### 2.1.4 Damage Effects on Anodize Coating (sulfuric anodize)

Aircraft structural aluminum is commonly installed with corrosion protection such as aluminum cladding or anodized coatings.

Qualitative examination of samples depainted in the SBIR Phase I program showed no effect on soft metal surfaces. Further tests to quantitatively demonstrate this observation were carried out in this Phase II program. Damage to such coatings has been reported with some presently available alternative cleaning technologies. Surface conductivity measurements will determine the degree to which anodized coatings are resistant to laser depainting.

The window of acceptable operating conditions for no damage to anodized coatings may differ from that found for bare aluminum or for composite materials. Samples of anodized material were subjected to laser energy of varying pulse frequency, energy density per pulse and pulse duration to supply data for definition of this operating window.

Electrical conductivity and corrosion tests were carried out to confirm the breakdown threshold for anodized films.

### 2.1.5 Material Balance Determination

The quantitative determination of amount and nature of decomposition products of paint removed by the application of laser energy provided data for the determination of potential waste disposal problems resulting from pulsed laser depainting.

The SBIR Phase I work indicated that most of the organic content of the paint being removed is converted to carbon dioxide and water. Material balance studies were conducted to confirm this observation and to give accurate data concerning the amount of potentially harmful off-gas products which must be collected by a filtration system.

The effect of increase or decrease in oxygen content of the gas surrounding the work piece on the nature of the off-gas products is unknown. It is conceivable that adjustment of the atmosphere surrounding the surface being depainted might obviate the need for an off-gas collection system. Such effects were examined but no final conclusions could be drawn prior to full scale operation since the concentrations of decomposition products were very low.

### 2.1.6 Temperature Rise Determination

The SBIR Phase I work showed no discernable temperature effects on the samples tested. As a part of this Phase II study, efforts were made to determine the temperatures reached by the surface of the substratum during the laser depainting process. The energy density of each pulse, the pulse duration, and the pulse frequency will all contribute to the heat build-up during paint stripping. Such heat build-up was determined over a range of input values which represent efficient paint stripping conditions.

### 2.1.7 Ultrasonic Inspection

The SBIR Phase I work showed that a substantial acoustic shockwave may be produced during the laser depainting process. The shock wave formed during the rapid vaporization of paint at the surface propagates through the sample reflecting off of the back surface and ultimately resulting in residual stresses in the substratum or the paint film interface. A number of suppliers of instrumentation were contacted and capabilities of their systems were investigated to determine their ability to detect the degree to which this shockwave is coupled to and transmitted through the substratum during the laser depainting process.

## 2.2 Phase II B Work

Phase II B work consists of those activities which required the use of higher powered equipment and equipment which more nearly models full scale units in both energy applied to the sample surface and in characteristics of the equipment.

#### 2.2.1 Electronics Damage Assessment

High powered lasers are known to produce electromagnetic pulses during operation. The high current flows result in high magnetic flux. This flux acts like a large induction field and will induce current flow in nearby conductors. The effect of such pulses on aircraft electronics must be determined in order to permit design of appropriate shielding.

#### 2.2.2 Noise Determination

A substantial acoustic shock wave is generated with each pulse of a laser depainting system. Systematic measurement of the external noise level was made to provide design data for appropriate remedies such as mufflers.

#### 2.2.3 Metallography and Fractography

Mechanical removal of paint by bead blasting causes cold working of the surface and potential damage depending on substratum thickness and loading. High power microscopic examination of laser depainted specimens investigated the presence or absence of similar effects with laser depainting.

#### 2.2.4 Qualitative Depainting Tests

Practical aircraft depainting will involve surfaces with a wide variety of contour irregularties and material configurations. Typical aircraft component samples were depainted to illustrate the practical capability of pulsed laser paint stripping.

#### 2.2.5 Spot Size and Beam Intensity Experiments

A series of tests were run with variation of the sample distance from the laser source with a divergent beam. This permitted development of understanding of the potential variable of spot size versus amount of paint removal per pulse. From such experiments operational variables for the cleaning of aircraft can be determined. Optimum depainting rates and optimum control of the degree of depainting may involve removal of a number of thin layers of the paint film rather than complete removal in a single laser shot of higher energy concentration.

#### 2.2.6 Tensile Strength Tests

Tensile strength of aircraft materials must not be degraded by paint removal procedures. While SBIR Phase I work showed no observable effects on the pulsed laser depainted substratum,

quantitative conformation will be required before the laser depainting technology can be safely applied to aircraft systems. Aluminum samples representative of aircraft skin materials were laser depainted then tensile tested to failure per ASTM E8.

#### 2.2.7 Fatigue Tests

Fatigue tests provide a measure of possible long term damage to aircraft materials. While SBIR Phase I work showed no observable effects on the pulsed laser depainted substratum, quantitative conformation will be required before the laser depainting technology can be safely applied to aircraft systems. Aluminum samples representative of aircraft skin materials were laser depainted then cyclically loaded to failure per ASTM E647.

#### 2.2.8 Residual Stress Tests

Residual stress tests provide a method for observing possible changes in materials particularly if such changes occur selectively in a surface layer. While SBIR Phase I work showed no observable effects on the pulsed laser depainted substratum, conformation will be required before the laser depainting technology can be safely applied to aircraft systems. Aluminum "Almen" strips were laser depainted then tested to see if any residual stress or hardening was present.

#### 2.2.9 Composite Tensile Tests

Aerospace composite materials consist of high strength fiber systems bound together by a material consisting of an organic resin such as epoxy. The resin is very similar in nature to the epoxy primers and polyurethane topcoats painted onto them. When the laser energy is powerful enough to volatilize the paint it can also vaporize the matrix resin. The critical question for laser effects on composites is; can the control mechanism stop the laser action before the mechanical performance of the composite is degraded because of removal of matrix resin? The second part of this question assumes knowledge of how much resin can be lost before unacceptable structural degradation occurs. With plastic media blasting the depainting process continues until the top coat is fully removed and residual primer is intact buffering the fibers. No visable fiber damage is permitted. The laser testing was constrained in a like manner. Depainting was controlled to permit topcoat removal but no visable fiber damage was allowed. Composite tensile tests were performed per ASTM D3039 to note the presence of fiber dominated property changes on graphite epoxy test specimens.

#### 2.2.10 Composite Flexural Strength Tests

The acoustic shock resulting from paint exploding or rapidly vaporizing off the surface caused concern over possible

microcracking or delamination effects due to the laser depainting. Flexural tests were conducted per ASTM D790 to determine if any detrimental effects were present. The flexural tests subject the inter-laminar or matrix dominated properties to stress loading and are used to identify delamination or crack related flaws in composite structures.

### 2.2.11 Composite Compressive Strength Tests

Compressive strength tests provide a further measure of possible damage to aircraft materials. While SBIR Phase I work showed no observable effects on the pulsed laser depainted substratum, quantitative conformation will be required before the laser depainting technology can be safely applied to air craft systems. Compression tests per ASTM D695 were performed to demonstrate the laser effects on composite materials.

### 2.2.12 Turbine Blade Cleaning

A small number of samples were tested to gain preliminary indications of the applicability of the laser cleaning methodology to other cleaning problems such as turbine blades and circuit boards.

### 2.2.13 Residual Carbon

Residual carbon resulting from incomplete removal of that portion of a paint film which had penetrated surface porosity during application has been identified as the source of potential corrosion problems with aluminum substrata. Test methods for the detection of such residual carbon are not well defined but efforts were made to develop techniques which would measure the magnitude of this problem as it may exist with a laser system. The corrosion tests defined the magnitude of this potential problem.

### 2.2.14 Analysis of Laser Paint Stripping System

An outline of a paint stripping system was developed utilizing a vision system and appropriate controls. This was done to support preliminary estimates of unit costs and capabilities of an operational system for paint removal on both aluminum and composite structures.

## 3.0 SAMPLE PROCUREMENT AND PREPARATION

### 3.1 Materials

The following materials were purchased as 4 ft x 12 ft sheets 0.032 in., from Electrolabs, Inc. of Warren, Michigan.

Aluminum alloy 2024-T3 bare
Aluminum alloy 2024-T3 bare anodized
Aluminum alloy 2024-T3 clad
Aluminum alloy 7075-T6 bare
Aluminum alloy 7075-T6 bare anodized
Aluminum alloy 7075-T6 clad

Composite samples were acquired as 2x2 ft. sheets of 16 ply material (IM6/3501-6) unidirectional Graphite/Epoxy. The sheets were prepared by University of Dayton Research Institute.

For fatigue crack growth tests a thin aluminum T-2024-T3 bare 0.016 in thick was purchased from Electrolabs, Inc.

### 3.2 Sample Identification

The as-received sheets were uniformly laid out for sample cutting into 2x2-ft. panels as shown on Figure 4.

Aluminum Alloy 2024-T3 bare.
Sheet No. 01
Panel Nos. 01-001 to 01-012

Aluminum alloy 2024-T3 bare anodized.
Sheet No. 02
Panel Nos. 02-001 to 02-012

Aluminum alloy 2024-T3 clad.
Sheet No. 03
Panel Nos. 03-001 to 03-012

Aluminum alloy 7075-T6 bare.
Sheet No. 04
Panel Nos. 04-001 to 04-012

Aluminum alloy 7075-T6 bare anodized.
Sheet No. 05
Panel Nos. 05-001 to 05-012

Aluminum alloy 7075-T6 clad.
Sheet No. 06
Panel Nos. 06-001 to 06-012

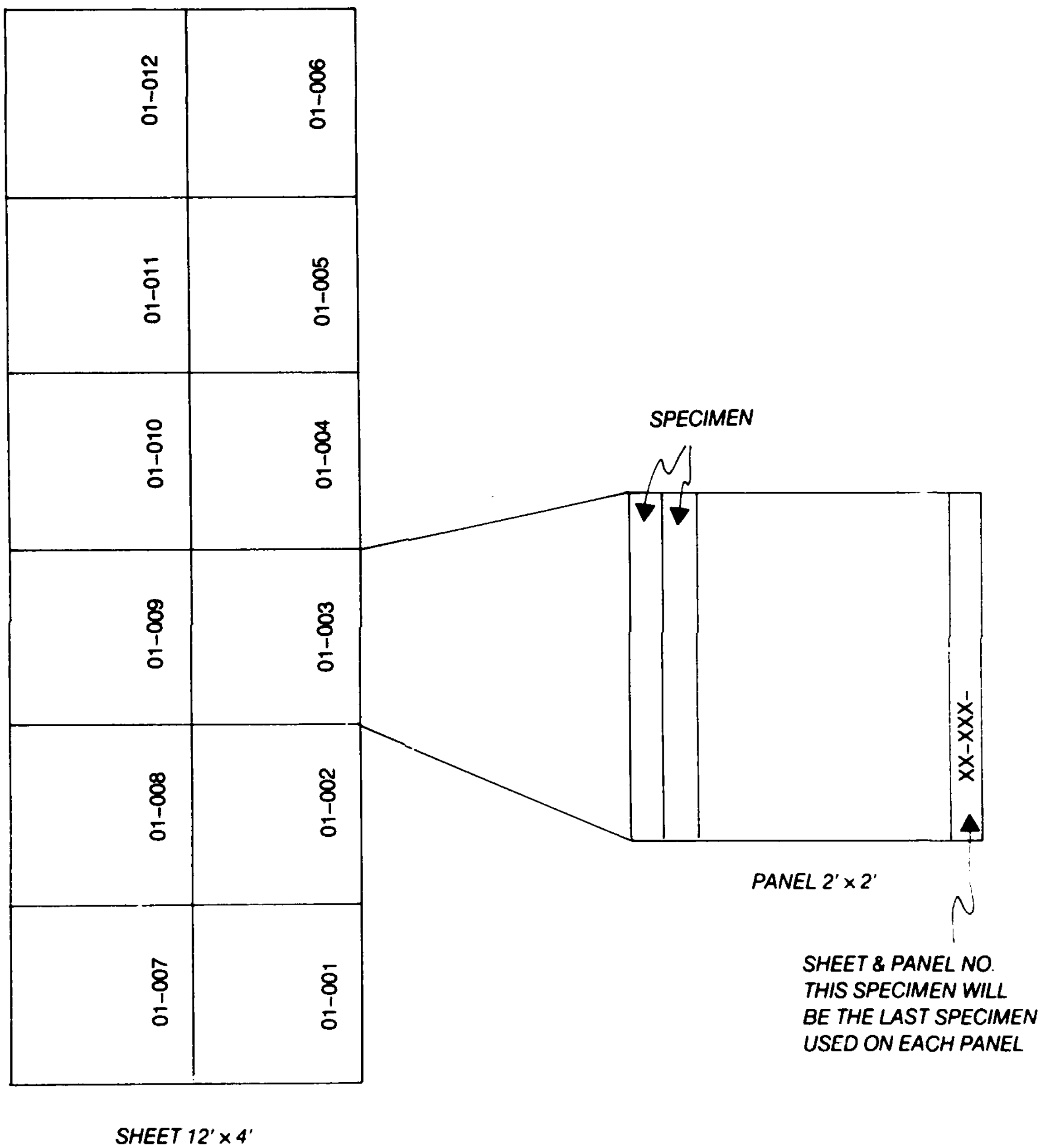



**Figure 4. Sheet Identification Scheme**

Epoxy-graphite composite material
Panel Nos. NF-001 to NF-010

Aluminum alloy 2024-T3 thin 0.016
Sheet No. NSA-001
Sample Nos.(3in.X12.5 in.) NSA-001-001 to 090

The 2x2-ft panels utilized in the program were further cut into samples as shown in Figure 5. The panels were all cut utilizing this common pattern and samples are numbered with a two digit sheet number followed by a three digit panel number and a four digit sample number. When samples were further subdivided such subdivision was done in a uniform manner as shown in Figure 6, with the subdivisions given the suffixes a-d following the sample number.

All samples were stored in individual envelopes together with sample data sheets for each treatment.

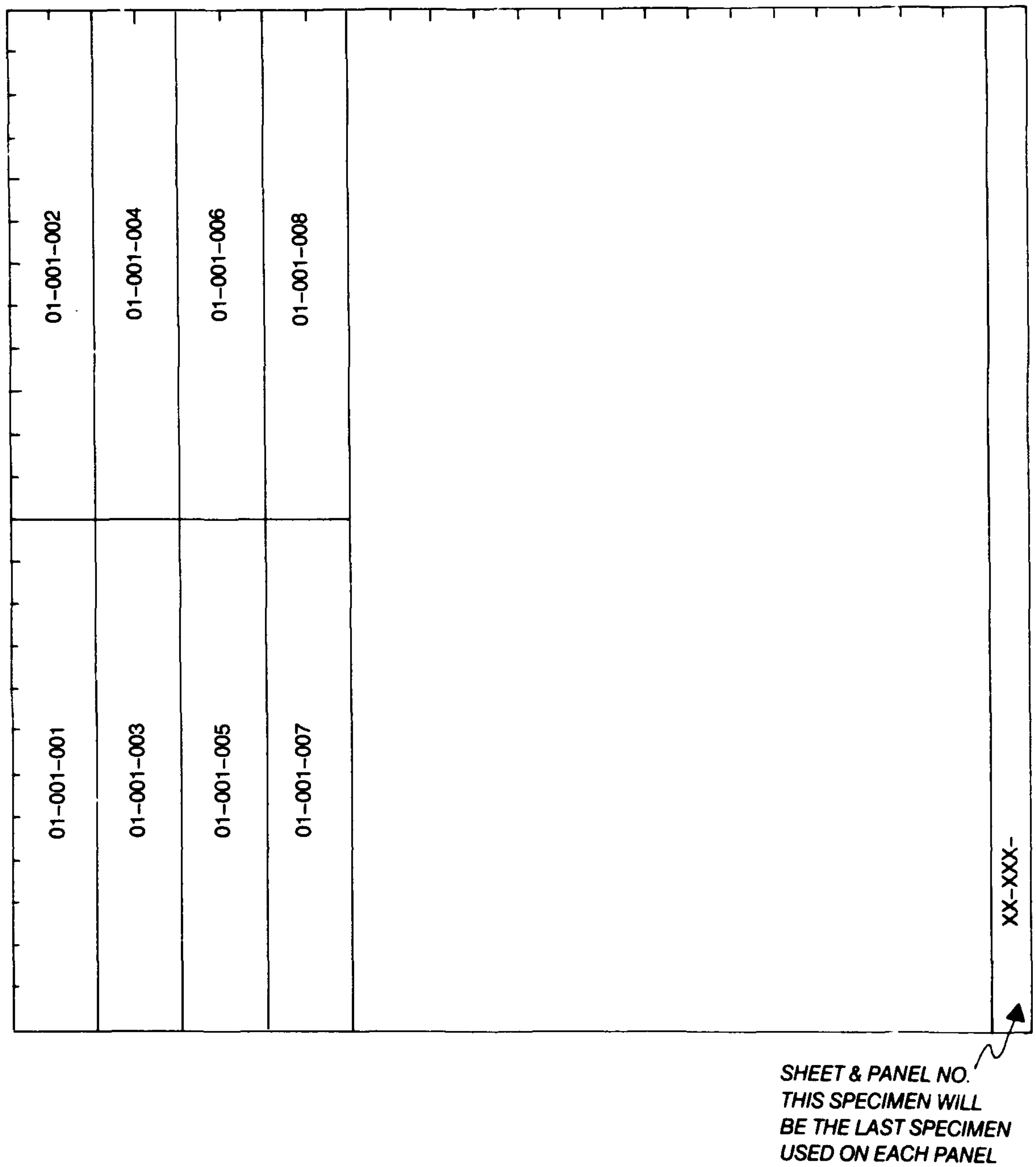



**Figure 5. Panel and Sample Numbering Scheme**

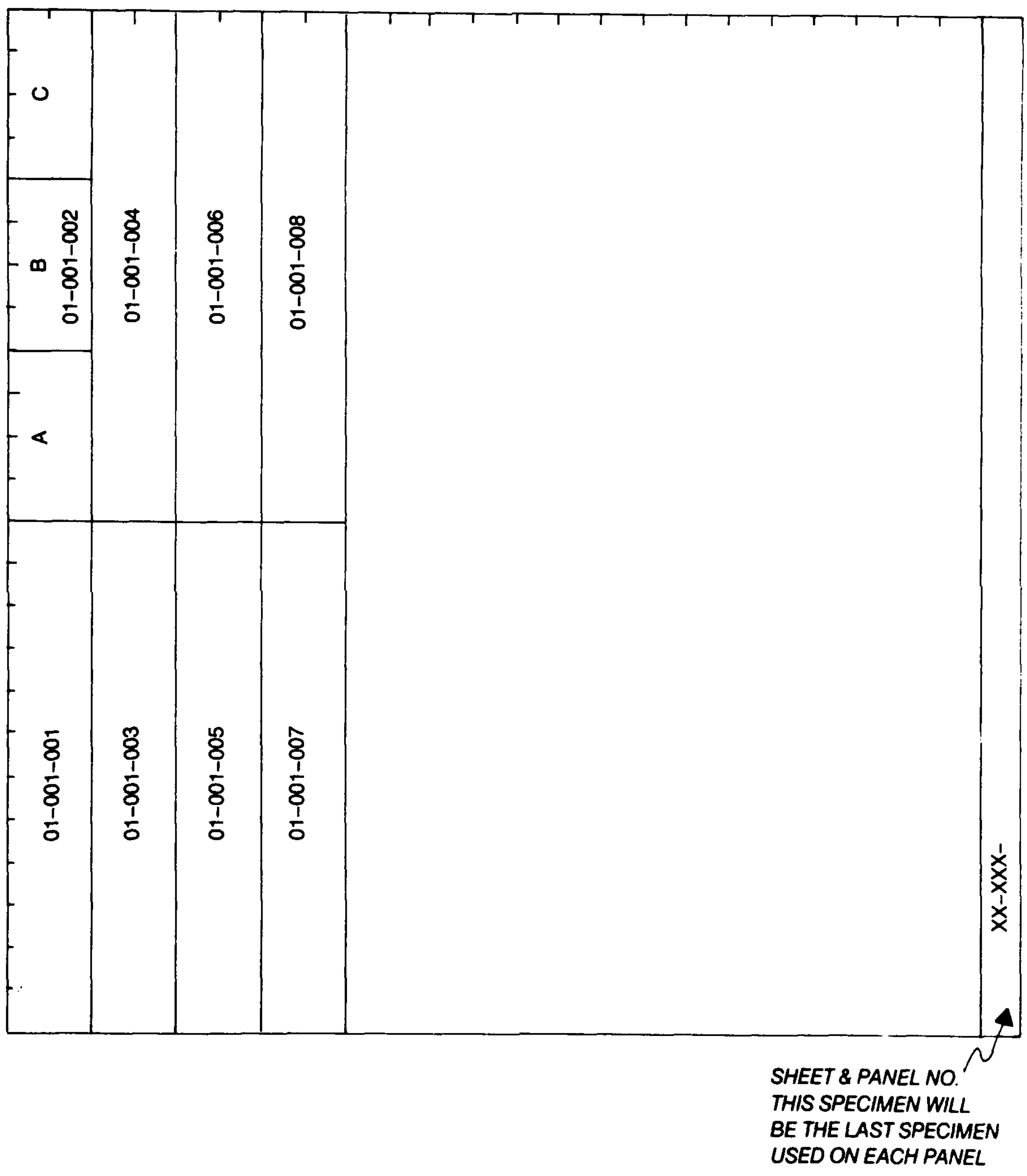



**Figure 6. Subsample Numbering Scheme**

## 3.3 Preparation

### 3.3.1 Aluminum Test Panels

a) All panels were alkaline detergent cleaned using MIL-C-25769 material.

b) The panels were deoxidized using material conforming to MIL-C-38334.

c) The panels were subjected to chemical conversion coating using material conforming to MIL-C-81706 and applied in accordance with MIL-C-5541.

d) The panels were primer coated to a dry film thickness of 0.0006 to 0.0009 inches with epoxy primer conforming to MIL-P-23377.

e) The panels were topcoated to a dry film thickness of 0.0017 to 0.0023 inches with urethane paint conforming to MIL-C-83286B.

f) The panels were ambient cured at 75 degrees F and 50% relative humidity for 7 days.

g) The panels were baked at 210 degrees F for 96 hours.

### 3.3.2 Graphite/Epoxy Composite Test Panels

a) The peel ply was removed.

b) The panels were immediately primer coated to a dry film thickness of 0.0006 to 0.0009 inches with epoxy primer conforming to MIL-P-23377.

c) The panels were topcoated to a dry film thickness of 0.0017 to 0.0023 inches with urethane paint conforming to MIL-C-83286B.

d) The panels were ambient cured at 75 degrees F and 50% relative humidity for 7 days.

e) The panels were baked at 210 degrees F for 96 hours.

### 3.3.3 Repaint Procedures - Aluminum Panels.

a) The panels were primer coated to a dry film thickness of 0.0006 to 0.0009 inches with epoxy primer conforming to MIL-P-23377.

b) The panels were topcoated to a dry film thickness of 0.0017 to 0.0023 inches with urethane paint conforming to MIL-C-83286B.

c) The panels were ambient cured at 75 degrees F and 50% relative humidity for 7 days.

d) The panels were baked at 210 degrees F for 96 hours.

### 3.3.4 Repaint Procedure-Graphite/Epoxy Composite

a) The panels were topcoated to a dry film thickness of 0.0017 to 0.0023 inches with urethane paint conforming to MIL-C-83286B.

b) The panels were ambient cured at 75 degrees F and 50% relative humidity for 7 days.

c) The panels were baked at 210 degrees F for 96 hours.

## 3.4 Paint Removal Energy Concentration

The energy utilized in removal of paint was recorded in terms of fluence (joules per sq cm per pulse)(J/sqcm) and either in number of pulses applied or as sufficient to expose the desired amount of primer layer or substratum.

The bulk of the work was done with standard operating conditions consisting of a pulse duration of 25 microseconds and a pulse frequency of 8 pulses per second. Other combinations of pulse frequency and pulse duration were studied to establish the conditions for most energy efficient paint removal. Sample temperature rise was measured over a range of laser input conditions to establish the comparability of such treatments to the substratum damage assessments obtained under the standard operating conditions.

# 4.0 SAMPLE PREPARATION AND TEST PROCEDURES

## 4.1 Painting Procedure

### 4.1.1 Precleaning

All as-received materials were inspected for surface contamination and dry wiped with clean cloth prior to painting.

### 4.1.2 Primer

Primer was applied with an air gun to specified thickness as noted in Section 3.3.

### 4.1.3 Paint

Paint was applied with an air gun to specified thickness as noted in Section 3.3.

## 4.2 Laser Paint Removal Procedure

Variation of distance from work piece permitted variation in fluence which is reported as joules per sq cm.

### 4.2.1 High Power single pulse equipment(system 1.4.1).

Sample was mounted on stationary holder and subjected to one or more pulses of laser energy.

### 4.2.2 Low Power Rapid Pulse Equipment(system 1.4.2)

Sample was mounted on a vertical x-y table and moved both horizontally and vertically to cover the area being cleaned. All cleaning at 8 pulses per second with pulse duration of 25 microseconds.

### 4.2.3 High Power Rapid Pulse Equipment(system 1.4.3)

Sample was placed on table and scanned with hand held beam delivery arm. Also, selected samples were moved by hand on a stationary stage under a fixed beam to insure constant energy level during measurement of heating and removal rates at varying pulse frequencies and duration.

## 4.3 Post Paint Removal Cleaning

Dry Wipe. Sample wiped thoroughly with clean cotton cloth.

Solvent Clean. Sample wiped thoroughly with cotton cloth soaked in naphtha-based paint thinner then dried at room temperature for 24 hours.

Detergent Clean. Sample wiped thoroughly with cotton cloth soaked in detergent solution, rinsed with clear water and dried at room temperature for 24 hours.

## 5.0 PAINT ADHESION

### 5.1 Tests Performed

**5.1.1A Wet Adhesion** (Tape Test), Method 6301, FED-STD-141, ASTM Method D. 3359-78.

Materials:

Aluminum alloy 2024-T3 bare
Aluminum alloy 2024-T3 clad
Aluminum alloy 2024-T3 bare anodized
Aluminum alloy 7075-T6 bare
Aluminum alloy 7075-T6 clad
Aluminum alloy 7075-T6 bare anodized
Unidirectional Graphite/epoxy composite

Five samples of each material were tested for paint adhesion in as-received condition to establish base line for comparison.

Five samples of each material were tested after laser cleaning and repainting at four levels of cleaning, first with cleaning only sufficient to expose approximately 10 percent of the primer i.e. paint was removed to expose 10% of the primer with the balance covered by residual thin layer of topcoat. Second the cleaning proceeded to the point where 50% of the primer was removed and the paint was essentially all removed. Third, the paint and primer were completely removed leaving bare metal. Finally, a small number of samples were depainted within the topcoat exposing no primer.

**5.1.1B Square and Diamond Pattern**

In order to increase sensitivity additional tests were conducted using a Precision Gauge and Tool Scriber test kit which produces closely spaced cuts through the paint film. A diamond pattern of crossed cuts was also used to insure maximum sensitivity.

All of these tests were run with complete removal of all paint and primer. Samples were repainted after laser cleaning with the following supplemental treatments:

a) Exposure to normal room conditions for 1 week
b) Exposure to normal room conditions for 3 days
c) Repaint immediately with no treatment
d) Repaint after dry wipe with clean cloth
e) Repaint after solvent wash
f) Repaint after detergent water wash

Specimen Preparation and Cleaning and Repaint Procedures: See Section 3.3.

## 5.2A Testing Results - Square Pattern

Depainted to expose 10% of primer.

Aluminum alloy 2024-T3 bare.

| Sample No. | Laser System | Fluence J/sqcm | Post Clean | Test Result |
|---|---|---|---|---|
| 01-010-0007 | Control | 0 | | Passed |
| 01-006-0007 | Control | 0 | | Passed |
| 01-004-0007 | Control | 0 | | Passed |
| 01-007-0007 | Control | 0 | | Passed |
| 01-004-0008 | Control | 0 | | Passed |
| 01-012-0005 | 1.4.2 | 20 | Dry Wipe | Passed |
| 01-009-0005 | 1.4.2 | 20 | Dry Wipe | Passed |
| 01-001-0005 | 1.4.2 | 20 | Dry Wipe | Passed |
| 01-003-0005 | 1.4.2 | 20 | Dry Wipe | Passed |
| 01-005-0005 | 1.4.2 | 20 | Dry Wipe | Passed |

Aluminum alloy 2024-T3 clad.

| Sample No. | Laser System | Fluence J/sqcm | Post Clean | Test Result |
|---|---|---|---|---|
| 03-002-0007 | Control | 0 | | Passed |
| 03-010-0007 | Control | 0 | | Passed |
| 03-006-0007 | Control | 0 | | Passed |
| 03-004-0008 | Control | 0 | | Passed |
| 03-007-0007 | Control | 0 | | Passed |
| 03-003-0005 | 1.4.2 | 20 | Dry Wipe | Passed |
| 03-012-0005 | 1.4.2 | 20 | Dry Wipe | Passed |
| 03-001-0005 | 1.4.2 | 20 | Dry Wipe | Passed |
| 03-009-0005 | 1.4.2 | 20 | Dry Wipe | Passed |
| 03-005-0005 | 1.4.2 | 20 | Dry Wipe | Passed |

Aluminum alloy 2024-T3 bare anodized.

| Sample No. | Laser System | Fluence J/sqcm | Post Clean | Test Result |
|---|---|---|---|---|
| 02-006-0007 | Control | 0 | | Failed |
| 02-010-0007 | Control | 0 | | Failed |
| 02-004-0007 | Control | 0 | | Failed |
| 02-004-0007? | Control | 0 | | Failed |
| 02-007-0007 | Control | 0 | | Failed |
| 02-001-0005 | 1.4.2 | 20 | Dry Wipe | Passed |
| 02-005-0005 | 1.4.2 | 20 | Dry Wipe | Passed |
| 02-003-0005 | 1.4.2 | 20 | Dry Wipe | Passed |
| 02-012-0005 | 1.4.2 | 20 | Dry Wipe | Passed |
| 02-009-0005 | 1.4.2 | 20 | Dry Wipe | Passed |

Aluminum alloy 7075-T6 bare.

| Sample No. | Laser System | Fluence J/sqcm | Post Clean | Test Result |
|---|---|---|---|---|
| 04-006-0007 | Control | 0 | | Passed |
| 04-007-0007 | Control | 0 | | Passed |
| 04-002-0007 | Control | 0 | | Passed |
| 04-010-0007 | Control | 0 | | Passed |
| 04-001-0005 | 1.4.2 | 20 | Dry Wipe | Passed |
| 04-003-0005 | 1.4.2 | 20 | Dry Wipe | Passed |
| 04-005-0005 | 1.4.2 | 20 | Dry Wipe | Passed |
| 04-009-0005 | 1.4.2 | 20 | Dry Wipe | Passed |
| 04-012-0005 | 1.4.2 | 20 | Dry Wipe | Passed |

Aluminum alloy 7075-T6 clad.

| Sample No. | Laser System | Fluence J/sqcm | Post Clean | Test Result |
|---|---|---|---|---|
| 06-004-0008 | Control | 0 | | Passed |
| 06-008-0008 | Control | 0 | | Passed |
| 06-007-0007 | Control | 0 | | Passed |
| 06-006-0007 | Control | 0 | | Passed |
| 06-010-0007 | Control | 0 | | Passed |
| 06-001-0005 | 1.4.2 | 20 | Dry Wipe | Passed |
| 06-003-0005 | 1.4.2 | 20 | Dry Wipe | Passed |
| 06-005-0005 | 1.4.2 | 20 | Dry Wipe | Passed |
| 06-009-0005 | 1.4.2 | 20 | Dry Wipe | Passed |
| 06-012-0005 | 1.4.2 | 20 | Dry Wipe | Passed |

Aluminum alloy 7075-T6 bare anodized.

| Sample No. | Laser System | Fluence J/sqcm | Post Clean | Test Result |
|---|---|---|---|---|
| 05-006-0007 | Control | 0 | | Failed |
| 05-007-0007 | Control | 0 | | Failed |
| 05-004-0007 | Control | 0 | | Failed |
| 05-004-0008 | Control | 0 | | Failed |
| 05-010-0007 | Control | 0 | | Failed |
| 05-001-0005 | 1.4.2 | 20 | Dry Wipe | Passed |
| 05-003-0005 | 1.4.2 | 20 | Dry Wipe | Passed |
| 05-005-0005 | 1.4.2 | 20 | Dry Wipe | Passed |
| 05-009-0005 | 1.4.2 | 20 | Dry Wipe | Passed |
| 05-012-0005 | 1.4.2 | 20 | Dry Wipe | Passed |

Depainted to remove 10% of primer.

Unidirectional Graphite/epoxy composite

| Sample No. | Laser System | Fluence J/sqcm | Post Clean | Test Result |
|---|---|---|---|---|
| NF-001-0006 | 1.4.2 | 20 | Dry Wipe | Passed |
| NF-002-0008 | 1.4.2 | 20 | Dry Wipe | Passed |
| NF-002-0009 | 1.4.2 | 20 | Dry Wipe | Passed |
| NF-002-0004 | 1.4.2 | 20 | Dry Wipe | Passed |
| NF-002-0006 | 1.4.2 | 20 | Dry Wipe | Passed |
| NF-001-0005 | 1.4.2 | 20 | Dry Wipe | Passed |
| NF-001-0008 | 1.4.2 | 20 | Dry Wipe | Passed |
| NF-002-0002 | 1.4.2 | 20 | Dry Wipe | Passed |
| NF-001-0004 | 1.4.2 | 20 | Dry Wipe | Passed |
| NF-002-0001 | 1.4.2 | 20 | Dry Wipe | Passed |

### 5.2B Testing Results - Diamond Pattern

Depainted to bare metal

Aluminum alloy 2024-T3 bare.

| Sample No. | Laser System | Fluence J/sqcm | Post Clean prior to repaint | Test Result |
|---|---|---|---|---|
| 01-008-0007B | 1.4.2 | 20 | Water Wash | Passed |
| 01-008-0007C | | Control | NA | Passed |
| 01-010-0008B | 1.4.2 | 20 | Water Wash | Passed |
| 01-010-0008C | | Control | NA | Passed |
| 01-008-0008B | 1.4.2 | 20 | Solvent Wash | Passed |
| 01-008-0008C | | Control | NA | Passed |
| 01-007-0008A | 1.4.2 | 20 | Detergent | Passed |
| 01-007-0008C | | Control | NA | Small flaking |
| 01-008-0007A | 1.4.2 | 20 | Detergent | Passed |
| 01-011-0007A | 1.4.2 | 20 | Detergent | Passed |
| 01-009-0004B | 1.4.2 | 20 | One week exp. | Passed |
| 01-009-0003B | 1.4.2 | 20 | One week exp. Dry Wipe | Passed |
| 01-009-0001B | 1.4.2 | 20 | One week exp. Solvent | Passed |
| The following were water soaked(1 hr) before testing. | | | | |
| 01-011-0007B | 1.4.2 | 20 | Water Washed | Passed |
| 01-011-0007C | | Control | NA | Passed |
| 01-008-0008A | 1.4.2 | 20 | Detergent | Passed |
| 01-007-0008B | 1.4.2 | 20 | Solvent | Passed |
| The following were water soaked(7 days) before testing. | | | | |
| 01-009-0005B | 1.4.2 | 20 | None | Passed |
| 01-009-0002B | 1.4.2 | 20 | Detergent | Failed |

Aluminum alloy 2024-T3 clad.

| Sample No. | Laser System | Fluence J/sqcm | Post Clean prior to repaint | Test Result |
|---|---|---|---|---|
| 03-006-0008A | 1.4.2 | 20 | Detergent | Passed |
| 03-005-0008B | 1.4.2 | 20 | None | Passed |
| 03-008-0008C | | Control | NA | Passed |
| The following were water soaked(1 hr) before testing. | | | | |
| 03-006-0008B | 1.4.2 | 20 | Solvent | Passed |
| 03-005-0008A | 1.4.2 | 20 | None | Passed |

Aluminum alloy 2024-T3 bare anodized.

| Sample No. | Laser System | Fluence J/sqcm | Post Clean prior to repaint | Test Result |
|---|---|---|---|---|
| 02-010-0008B | 1.4.2 | 20 | Solvent | Passed |
| 02-008-0008A | 1.4.2 | 20 | Detergent | Passed |
| 02-008-0008C | | Control | NA | Passed |
| The following were water soaked(1 hr) before testing. | | | | |
| 02-010-0008A | 1.4.2 | 20 | Detergent | Passed |
| 02-010-0008C | | Control | NA | Passed |
| The following were water soaked(7 days) before testing. | | | | |
| 02-001-0005B | 1.4.2 | 20 | None | Passed |

### 5.2C Adhesion to partially removed paint film.

Samples were stripped with varying fluence leaving both primer and some paint. Stripped samples were repainted and subjected to standard adhesion test. All samples stripped with system 1.4.2. and then repainted with no intermediate cleaning.

| Sample No. | Fluence J/sqcm | Test Result Dried | Test Result after water soak for 7 days |
|---|---|---|---|
| 01-006-0007A | 23 | Passed | Passed |
| 01-006-0004B | 11 | Passed | Passed |
| 02-007-0007C | 23 | Passed | Some peeling |
| 02-002-0003C | 11 | Passed | Serious peeling |
| 02-002-0003B | 17 | Passed | Serious peeling |
| 04-003-0004B | 17 | Passed | Some peeling |

### 5.3 Conclusions

Aluminum alloy 2024-T3 bare
Aluminum alloy 2024-T3 clad
Aluminum alloy 2024-T3 bare anodized
Aluminum alloy 7075-T6 bare
Aluminum alloy 7075-T6 clad
Aluminum alloy 7075-T6 bare anodized
All samples equal to or better than control.

Unidirectional Graphite/epoxy composite
All samples equal to or better than control.

### 5.3B Diamond pattern test

Aluminum alloy 2024-T3 bare.
Aluminum alloy 2024-T3 bare anodized.
Aluminum alloy 2024-T3 clad.
Aluminum alloy 7075-T6 bare.
Aluminum alloy 7075-T6 bare anodized.
Aluminum alloy 7075-T6 clad.

All samples equal to or better than control.

Unidirectional Graphite/epoxy composite

All samples equal to or better than control.

The tests provide conclusive evidence that in-so-far as adhesion is concerned, laser depainting under the conditions of these experiments causes no negative effects and may enhance adhesion.

## 6.0 CORROSION TESTS

### 6.1 Tests Performed

Corrosion Test: I.A.W. ASTM B-117 and ASTM D-2247.

Exposure in a 5% neutral salt spray at 95 degrees C.

Materials:

- Aluminum alloy 2024-T3 bare
- Aluminum alloy 2024-T3 clad
- Aluminum alloy 2024-T3 bare anodized
- Aluminum alloy 7075-T6 bare
- Aluminum alloy 7075-T6 clad
- Aluminum alloy 7075-T6 bare anodized
- Unidirectional Graphite/epoxy composite.

Number of samples:

Five samples of each material to be tested in as received condition to establish base line for comparison.

Five samples of each material to be tested after laser depainting to remove all surface paint and approximately 50 percent of the primer and repriming and repainting.

Tests were repeated using five samples each of bare and anodized 2024-T3 for each of the following post laser cleaning procedures.

a) No further cleaning
b) Dry wipe
c) Detergent wash and dry
d) Solvent wash

Specimen Preparation and Cleaning and Repaint Procedures: See Section 3.3.

### 6.2 Test Results

#### 6.2.1 (a) Corrosion Test I.A.W. ASTM B-117

Exposure in a neutral 5% salt spray, take periodic observations.

Aluminum alloy 2024-T3 bare. Urethane paint. Depainted with laser system 1.4.2.

| Sample No. | Fluence | Post Clean | Exposure | Test Result |
|---|---|---|---|---|
| 01-003-0008 | Control | NA | 336 hours | No change |
| 01-012-0008 | Control | NA | 336 hours | No change |
| 01-011-0008 | Control | NA | 336 hours | No change |
| 01-002-0005 | | None | 336 hours | No change |
| 01-008-0005 | | None | 336 hours | No change |
| 01-010-0005 | | None | 336 hours | No change |
| 01-009-0003A | | Detergent | 504 hours | Slight Blistering |

| Sample No. | Fluence | Post Clean | Exposure | Test Result |
|---|---|---|---|---|
| 01-009-0002A | | Solvent | 504 hours | No Change |
| 01-006-0006B | | Solvent | 504 hours | No Change |
| 01-006-0004A | | Dry Wipe | 504 hours | No Change |
| 01-009-0005A | | Dry Wipe | 504 hours | No Change |
| 01-006-0007B | | Dry Wipe | 504 hours | No Change |
| 01-009-0007C | | Dry Wipe | 5C4 hours | No Change |
| 01-006-0005A | | None | 504 hours | No Change |
| 01-006-0006A | | None | 504 hours | No Change |
| 01-009-0007B | | None | 504 hours | No Change |
| 01-006-0007C | | None | 504 hours | No Change |

All samples showed slight blistering after 720 hours

Aluminum alloy 2024-T3 bare anodized. Urethane paint. Depainted with laser system 1.4.2.

| Sample No. | Fluence | Post Clean | Exposure | Test Result |
|---|---|---|---|---|
| 02-003-0008 | Control | NA | 336 hours | No change |
| 02-011-0008 | Control | NA | 336 hours | No change |
| 02-012-0008 | Control | NA | 336 hours | No change |
| 02-004-0005 | | NA | 336 hours | No change |
| 02-002-0005 | | NA | 336 hours | No change |
| 02-008-0005 | | NA | 336 hours | No change |
| 02-005-0002A | | Detergent | 504 hours | No Change |
| 02-001-0003A | | Detergent | 504 hours | Slight Blistering |
| 02-005-0006B | | Detergent | 504 hours | No Change |
| 02-001-0006C | | Detergent | 504 hours | No Change |
| 02-005-0001A | | Solvent | 504 hours | No Change |
| 02-001-0002A | | Solvent | 504 hours | No Change |
| 02-005-0006C | | Solvent | 504 hours | No Change |
| 02-001-0004A | | Dry Wipe | 504 hours | No Change |
| 02-005-0005A | | None | 504 hours | No Change |

All samples showed slight blistering after 720 hours

Aluminum alloy 2024-T3 clad. Urethane paint. Depainted with laser system 1.4.2.

| Sample No. | Fluence J/sqcm | Post Clean | Exposure | Test Result |
|---|---|---|---|---|
| 03-012-0008 | Control | NA | 336 hours | No change |
| 03-011-0008 | Control | NA | 336 hours | No change |
| 03-003-0008 | Control | NA | 336 hours | No change |
| 03-010-0005 | | NA | 336 hours | No change |
| 03-002-0005 | | NA | 336 hours | No change |

Aluminum alloy 7075-T6 bare. Urethane paint. Depainted with laser system 1.4.2.

| Sample No. | Fluence J/sqcm | Post Clean | Exposure | Test Result |
|---|---|---|---|---|
| 04-012-0008 | Control | NA | 336 hours | No change |
| 04-011-0008 | Control | NA | 336 hours | No change |
| 04-002-0008 | Control | NA | 336 hours | No change |
| 04-010-0005 | | NA | 336 hours | No change |
| 04-002-0005 | | NA | 336 hours | No change |
| 04-004-0005 | | NA | 336 hours | No change |

Aluminum alloy 7075-T6 clad. Urethane paint.
Depainted with laser system 1.4.2.

| Sample No. | Fluence J/sqcm | Post Clean | Exposure | Test Result |
|---|---|---|---|---|
| 06-012-0008 | Control | NA | 336 hours | No change |
| 06-001-0008 | Control | NA | 336 hours | No change |
| 06-003-0008 | Control | NA | 336 hours | No change |
| 06-008-0005 | | NA | 336 hours | No change |
| 06-002-0005 | | NA | 336 hours | No change |
| 06-004-0005 | | NA | 336 hours | No change |

Aluminum alloy 7075-T6 bare anodized. Urethane paint.
Depainted with laser system 1.4.2.

| Sample No. | Fluence J/sqcm | Post Clean | Exposure | Test Result |
|---|---|---|---|---|
| 05-010-0008 | Control | NA | 336 hours | No change |
| 05-008-0008 | Control | NA | 336 hours | No change |
| 05-003-0008 | Control | NA | 336 hours | No change |
| 05-007-0005 | | NA | 336 hours | No change |
| 05-002-0005 | | NA | 336 hours | No change |
| 05-004-0005 | | NA | 336 hours | No change |

**6.2.2(b) Corrosion Test - Humidity** - ASTM D-2247.
Exposure in high humidity chamber, take periodic observations.

Aluminum alloy 2024-T3 bare. Urethane paint.
Depainted with laser system 1.4.2.

| Sample No. | Fluence J/sqcm | Post Clean | Exposure | Test Result |
|---|---|---|---|---|
| 01-002-0007 | Control | NA | 336 hours | Fine blisters |
| 01-002-0008 | Control | NA | 336 hours | No change |
| 01-007-0008 | 14 | NA | 336 hours | No change |
| 01-004-0007 | 14 | NA | 336 hours | No change |
| 01-006-0002A | 14 | Detergent | 504 hours | Moderate blistering |
| 01-006-0003A | 14 | Detergent | 504 hours | Moderate blistering |
| 01-009-0006B | 14 | Detergent | 504 hours | Moderate Blistering |
| 01-006-0006C | 14 | Detergent | 504 hours | Slight Blistering |
| 01-006-0001A | 14 | Solvent | 504 hours | No Change |
| 01-009-0001A | 14 | Solvent | 504 hours | No Change |
| 01-009-0006C | 14 | Solvent | 504 hours | No Change |
| 01-009-0004A | 14 | Dry Wipe | 504 hours | No Change |
| 01-009-0006A | 14 | None | 504 hours | No Change |

All samples showed slight blistering after 720 hours

Aluminum alloy 2024-T3 clad. Urethane paint.
Depainted with laser system 1.4.2.

| Sample No. | Fluence J/sqcm | Post Clean | Exposure | Test Result |
|---|---|---|---|---|
| 03-004-0007 | Control | NA | 336 hours | No change |
| 03-002-0008 | Control | NA | 336 hours | No change |
| 03-007-0005 | 14 | NA | 336 hours | No change |
| 03-008-0005 | 14 | NA | 336 hours | No change |

Aluminum alloy 2024-T3 bare anodized. Urethane paint.
Depainted with laser system 1.4.2.

| Sample No. | Fluence J/sqcm | Post Clean | Exposure | Test Result |
|---|---|---|---|---|
| 02-002-0007 | Control | NA | 336 hours | Delamination |
| 02-002-0008 | Control | NA | 336 hours | Dense blisters |
| 02-007-0005 | 14 | NA | 336 hours | No change |
| 02-010-0005 | 14 | NA | 336 hours | No change |
| 02-005-0003A | 14 | Detergent | 504 hours | No Change |
| 02-001-0001A | 14 | Solvent | 504 hours | No Change |
| 02-001-0006B | 14 | Solvent | 504 hours | Slight Blistering |
| 02-005-0004A | 14 | Dry Wipe | 504 hours | No Change |
| 02-001-0005A | 14 | Dry Wipe | 504 hours | Slight Blistering |
| 02-001-0007B | 14 | Dry Wipe | 504 hours | No Change |
| 02-005-0007C | 14 | Dry Wipe | 504 hours | No Change |
| 02-001-0006A | 14 | None | 504 hours | No Change |
| 02-005-0006A | 14 | None | 504 hours | No Change |
| 02-005-0007B | 14 | None | 504 hours | Slight Blistering |
| 02-001-0007C | 14 | None | 504 hours | No Change |

All samples showed slight blistering after 720 hours

Aluminum alloy 7075-T6 bare. Urethane paint.
Depainted with laser system 1.4.2.

| Sample No. | Fluence J/sqcm | Post Clean | Exposure | Test Result |
|---|---|---|---|---|
| 04-004-0007 | Control | NA | 336 hours | No change |
| 04-003-0008 | Control | NA | 336 hours | No change |
| 04-007-0005 | 14 | NA | 336 hours | No change |
| 04-008-0005 | 14 | NA | 336 hours | No change |

Aluminum alloy 7075-T6 clad. Urethane paint.
Depainted with laser system 1.4.2.

| Sample No. | Fluence J/sqcm | Post Clean | Exposure | Test Result |
|---|---|---|---|---|
| 06-002-0007 | Control | NA | 336 hours | Fine blisters |
| 06-002-0008 | Control | NA | 336 hours | No change |
| 06-007-0005 | 14 | NA | 336 hours | No change |
| 06-010-0005 | 14 | NA | 336 hours | No change |

Aluminum alloy 7075-T6 bare anodized. Urethane paint. Depainted with laser system 1.4.2.

| Sample No. | Fluence J/sqcm | Post Clean | Exposure | Test Result |
|---|---|---|---|---|
| 05-002-0007 | Control | NA | 336 hours | Dense blisters |
| 05-002-0008 | Control | NA | 336 hours | Delamination |
| 05-008-0005 | 14 | NA | 336 hours | No change |
| 05-010-0005 | 14 | NA | 336 hours | No change |

### 6.3 Conclusions

On corrosion and humidity tests the laser depainted samples significantly outperformed control samples. The use of standard cleaning procedures after laser depainting and prior to painting caused significant increase in susceptibility to corrosion. This loss of cleanliness was particularly notable when applying the standard detergent cleaning process.

We can conclude that materials should be painted directly after laser depainting with no intermediate washing or other cleanup procedures. The use of current standard pre-painting cleaning procedures after laser stripping made no contribution to resistance to salt spray and humidity tests. There is clear evidence that laser depainting with immediate repainting supplies superior performance in comparison with current procedures.

## 7.0 SURFACE ROUGHNESS

### 7.1 Tests Performed

Surface roughness measurements to be taken with a Surtronic 3 manufactured by Rank-Taylor-Hobson. Each data point to represent the average of 10 readings (in microinches) taken every 0.03 inches over 0.30 inches travel of the probe. Five data points to be taken on each specimen.

Materials:

- Aluminum alloy 2024-T3 bare
- Aluminum alloy 2024-T3 clad
- Aluminum alloy 2024-T3 bare anodized
- Aluminum alloy 7075-T6 bare
- Aluminum alloy 7075-T6 clad
- Aluminum alloy 7075-T6 bare anodized

Number of samples:

Three samples of each material to be tested in as received condition to establish base line for comparison.

Three samples of each material to be tested after laser depainting to remove all surface paint and approximately 50 percent of primer.

Specimen Preparation and Cleaning Procedures: See Section 3.3.

### 7.2 Testing Results

Aluminum alloy 2024-T3 bare.

| Sample No. | | Laser System | Fluence J/sqcm | Test Result Average Ra Value |
|---|---|---|---|---|
| 01-009-0004 | As received | | | 16.1 |
| 01-011-0001 | As received | | | 13.8 |
| 01-011-0002 | As received | | | 12.9 |
| 01-001-0008 | Laser Cleaned | 1.4.2 | 20 | 10.8 |
| 01-006-0005 | Laser Cleaned | 1.4.2 | 20 | 10.8 |
| 01-006-0006 | Laser Cleaned | 1.4.2 | 20 | 9.0 |

Aluminum alloy 2024-T3 clad.

| Sample No. | | Laser System | Fluence J/sqcm | Test Result Average Ra Value |
|---|---|---|---|---|
| 03-009-0004 | As received | | | 20.3 |
| 03-011-0001 | As received | | | 22.8 |
| 03-011-0002 | As received | | | 22.4 |
| 03-001-0008 | Laser Depainted | 1.4.2 | 20 | 13.5 |
| 03-006-0005 | Laser Depainted | 1.4.2 | 20 | 15.0 |
| 03-006-0006 | Laser Depainted | 1.4.2 | 20 | 16.9 |

Aluminum alloy 2024-T3 bare anodized.

| Sample No. | | Laser System | Fluence J/sqcm | Test Result Average Ra Value |
|---|---|---|---|---|
| 02-009-0004 | As received | | | 24.7 |
| 02-011-0001 | As received | | | 44.2 |
| 02-011-0002 | As received | | | 47.6 |
| 02-001-0008 | Laser Depainted | 1.4.2 | 20 | 23.1 |
| 02-006-0005 | Laser Depainted | 1.4.2 | 20 | 31.1 |
| 02-006-0006 | Laser Depainted | 1.4.2 | 20 | 25.3 |

Aluminum alloy 7075-T6 bare.

| Sample No. | | Laser System | Fluence J/sqcm | Test Result Average Ra Value |
|---|---|---|---|---|
| 04-009-0004 | As received | | | 18.6 |
| 04-011-0001 | As received | | | 18.1 |
| 04-011-0002 | As received | | | 11.7 |
| 04-001-0008 | Laser Depainted | 1.4.2 | 20 | 10.9 |
| 04-006-0005 | Laser Depainted | 1.4.2 | 20 | 12.3 |
| 04-006-0006 | Laser Depainted | 1.4.2 | 20 | 11.0 |

Aluminum alloy 7075-T6 clad.

| Sample No. | | Laser System | Fluence J/sqcm | Test Result Average Ra Value |
|---|---|---|---|---|
| 06-009-0004 | As received | | | 5.2 |
| 06-011-0001 | As received | | | 10.0 |
| 06-011-0002 | As received | | | 8.1 |
| 06-001-0008 | Laser Depainted | 1.4.2 | 20 | 5.1 |
| 06-006-0005 | Laser Depainted | 1.4.2 | 20 | 7.3 |
| 06-006-0006 | Laser Depainted | 1.4.2 | 20 | 6.2 |

Aluminum alloy 7075-T6 bare anodized.

| Sample No. | | Laser System | Fluence J/sqcm | Test Result Average Ra Value |
|---|---|---|---|---|
| 05-009-0004 | As received | | | 17.6 |
| 05-011-0001 | As received | | | 19.0 |
| 05-011-0002 | As received | | | 21.9 |
| 05-001-0008 | Laser Depainted | 1.4.2 | 20 | 19.6 |
| 05-006-0005 | Laser Depainted | 1.4.2 | 20 | 40.6 |
| 05-006-0006 | Laser Depainted | 1.4.2 | 20 | 19.6 |

### 7.3 Conclusions

Surface roughness varies with each of the above materials but in all cases appeared to be decreased by painting and subsequent laser removal of the paint. The laser depainting retains the smoothness of the original paint film and leaves the holes filled.

## 8.0 DAMAGE TO ANODIZED COATINGS

### 8.1 Tests Performed

Sulfuric Acid Anodized Material, MIL-A-8625D, Type II
This represents the bulk of all Air Force usage.

Test procedure:
Using 300 grit sand paper, lightly remove all anodized coating from a small area. Contact sanded area with one electrode of a volt/ohm meter and move the other electrode over the area to be inspected for damage to the anodized coating. Any deflection of the meter indicates damage.

Materials:
- Aluminum alloy 2024 bare anodized
- Aluminum alloy 2024 clad anodized
- Aluminum alloy 7075 bare anodized
- Aluminum alloy 7075 clad anodized

Number of samples:

Three samples of each material were tested in as-received unpainted condition to establish base line for comparison.

Samples of each material were tested after painting and laser depainting to bare metal. Exact number of pulses was determined at time of test to record the number of pulses required to expose bare metal.

Tests were repeated with variation of energy impinging on the surface to be cleaned from 1 joule per sq cm to 20 joules per sq cm. Tests were done both on as received unpainted samples and after removal of paint.

After repainting, further tests were run by the corrosion test procedure to determine possible loss of corrosion resistance.

Specimen Preparation and Cleaning and Repaint Procedures: See Section 3.3.

### 8.2 Testing Results

Preliminary range finding tests showed the possibility of damage to the anodized coating when utilizing the very short (less than 2 microsecond) pulse laser (Section 1.4.1). Samples, from which paint was removed with this equipment, showed areas of electrical conductivity. When these experiments were repeated using the longer pulse duration equipment (Section 1.4.2 and 1.4.3) no electrical conductivity could be detected in laser cleaned areas.

| Sample No. | Laser System | Pulse Duration | Fluence J/sqcm | No. of Pulses | Resistance Ohms |
|---|---|---|---|---|---|
| 02-004-0003 | 1.4.1 | 1 ms | 8 | 6 | 0.1 |
| 02-004-0003 | 1.4.1 | 1 ms | 8 | 7 | 0.3 |
| 02-007-0003 | 1.4.1 | 1 ms | 8 | 6 | 0.0 |
| 05-004-0004 | 1.4.1 | 1 ms | 8 | 5 | 0.3 |
| 05-006-0004 | 1.4.1 | 1 ms | 8 | 7 | 0.2 |
| 05-007-0004 | 1.4.1 | 1 ms | 8 | 7 | 0.6 |
| 05-011-0004 | 1.4.2 | 25 ms | 28 | 1 | No Cond. |
| 05-011-0004 | 1.4.2 | 25 ms | 23 | 1 | No Cond. |
| 05-011-0003 | 1.4.2 | 25 | 23 | 25 | No Cond. |
| 05-011-0004 | 1.4.2 | 25 ms | 21 | 1 | No Cond. |
| 05-011-0004 | 1.4.2 | 25 ms | 18 | 1 | No Cond. |
| 05-011-0004 | 1.4.2 | 25 ms | 14 | 1 | No Cond. |
| 05-011-0004 | 1.4.2 | 25 ms | 11 | 1 | No Cond. |
| 05-011-0004 | 1.4.2 | 25 ms | 9 | 1 | No Cond. |
| 05-011-0004 | 1.4.2 | 25 ms | 7 | 1 | No Cond. |
| 05-011-0004 | 1.4.2 | 25 ms | 5 | 1 | No Cond. |
| 05-011-0004 | 1.4.2 | 25 ms | 4 | 1 | No Cond. |
| 05-011-0004 | 1.4.2 | 25 ms | 3 | 1 | No Cond. |
| 02-004-0003 | 1.4.3 | 16 ms | 7 | 3000 | No Cond. |
| 02-004-0003 | 1.4.3 | 12 ms | 5 | 3000 | No Cond. |
| 05-012-0004 | 1.4.3 | 16 ms | 5 | 500 | No Cond. |

The lack of conductivity is an indication of no gross damage to the anodizing layer. The retention of the protective properties is also indicated by other tests. Anodized samples were depainted and repainted and then subjected to corrosion and humidity tests as defined and reported in Section 6.1.2(a) and 6.1.2(b).

All exposure of anodizing to laser energy showed a change in surface appearance. Micro photos of stripped and unstripped surfaces are presented in Figures 7-8.

Sample #02-005-0007

Magnification 100x

Cross sectional view of the prepared surface. Left side of photo shows the stripped surface. Right side of photo shows the unstripped surface.

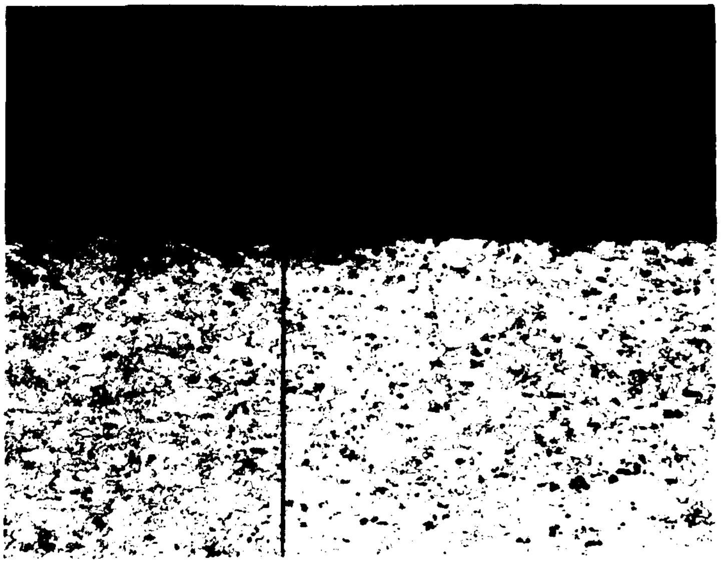


**Figure 7. 2024-T3 bare anodized**

Sample #05-006-0008

Magnification 100x

Cross sectional view of the prepared surface. Left side of photo shows the stripped surface. Right side of photo shows the unstripped surface.

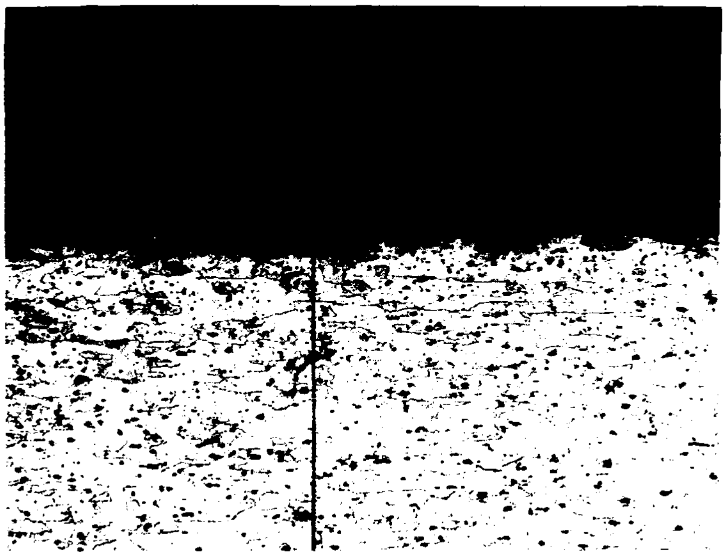


**Figure 8. 7075 T6 bare anodized**

### 8.3 Conclusions

Aluminum alloy 2024 bare anodized
Aluminum alloy 7075 bare anodized

Significant damage to hard sulfuric acid anodize coatings occurs during pulsed laser paint removal using pulse durations of less than 2 microseconds. This damage appears to be associated with the initiation of a shock wave in the substratum material causing damage to the bond between the substratum material and the anodized coating. The damage occurs independently of the energy density applied.

At pulse duration of 25 microseconds and energy density of 5-25 Joules per sqcm per pulse no damage to sulfuric acid anodizing of Aluminum alloy 2024 bare anodized or Aluminum alloy 7075 bare anodized could be detected.

## 9.0 MATERIAL BALANCE

### 9.1 Tests Performed

In Phase IIA range finding experiments were conducted to gain knowledge for definitive experiments under Phase IIB. These preliminary experiments consisted of removal of paint from samples in a totally enclosed chamber so that all gases evolved could be captured and measured. Measurements included total weight loss of the sample being depainted total non-condensable gases evolved, and total weight of condensables deposited on the walls of the chamber. Samples washed from the walls of the chamber were examined to determine the nature and relative amounts of various molecular weight fractions.

Final studies under Phase IIB involved duplicate experiments in which samples prepared as defined in Section 3.3 were depainted down to 50 percent removal of primer and all decomposition products collected and identified to the extent warranted to support design of collection equipment to meet NIOSH and OSHA standards. Experiments were repeated with both urethane and epoxy paints and in the case of the urethane paint with air, nitrogen and oxygen as cover gases.

Equipment design is shown in Figure 9.

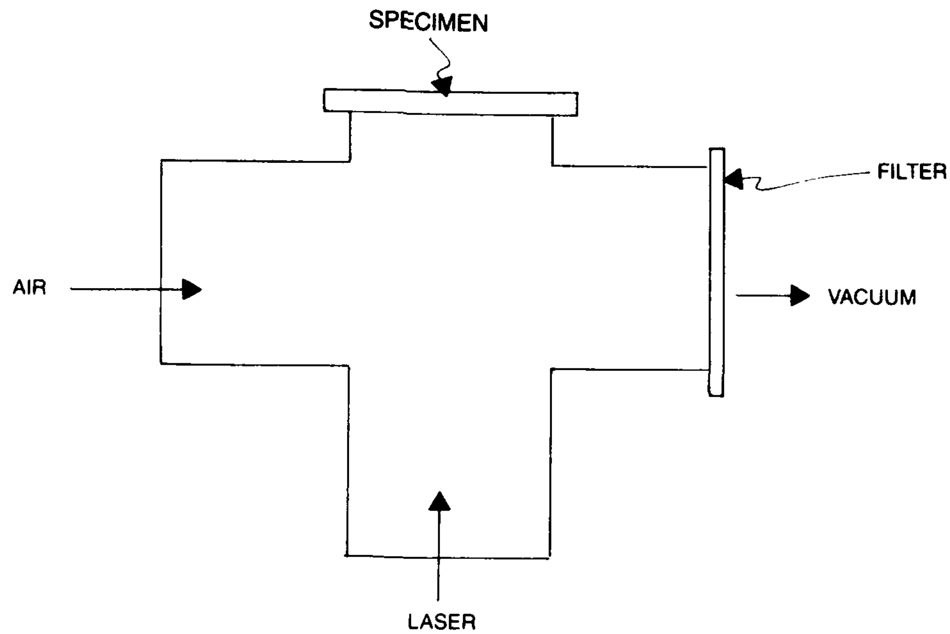



**Figure 9. Material Balance Equipment**

### 9.2 Testing Results

Standard primer and finish coat dry paint samples were ashed to determine the total non-combustable content of each.
Primer 54.9% ash
Paint 31.4% ash

Samples depainted with equipment 1.4.2 with off gas collected through a 0.6 micron filter showed the following results:

Primer 42% to 44% of weight of primer removed collected on filter.

Paint 32% to 35% of weight of paint removed collected on filter.

Utilizing the high powered laser (1.4.3) larger samples of the solids given off during removal of each of paint and primer were collected and subjected to analysis.

Paint- Solids analysed by TGA showed weight loss of 18% of which 0.15% was moisture as determined by Fischer Coulometric analysis. The difference is assumed to be organic materials, i.e. tars produced in the paint combustion. Thus about 95 percent of the organic paint binder removed was converted to $CO_2$ and water or other volatile constituents not captured by the 0.6 micron filter system.

Primer- Solids analysed by TGA showed weight loss of 4% of which 0.23% was moisture as determined by Fischer Coulometric analysis. The difference is assumed to be organic materials, i.e. tars produced in the paint combustion. Thus again over 95 percent of the organic paint binder removed was converted to $CO_2$ and water or other volatile constituents not captured by the 0.6-micron filter system.

A series of experiments were run depainting in an oxygen atmosphere. Such experiments gave no indication of change in off-gas products.

As a contribution to future system development, design studies of the filtration requirements of the waste gas stream were undertaken. The analytical samples were collected on 0.6 micron filters. Use of a commercially available, Viledon MF 95, filter ahead of the laboratory filter collected all waste products and no material penetrated to the laboratory filter.

### 9.3 Conclusions

Results show that solids equal to the pigment content of the coating being removed are collectable. These solids have only traces of organic material indicating that the organic content of the paint film is largely converted to $CO_2$ and water.

The intermitment and small sample availability made it impossible to fully study the nature of and problems associated with the off-gas stream. The data indicate that the composition of the off

gas will be highly dependent on air flow rates to the combustion zone immediately in the vicinity of the surface being cleaned. At low flow rates, under 1 ft per second, the plume interferes with the next incoming pulse of laser energy and gives low paint removal efficiency. At flow rates of 1-3 ft per second the paint removed undergoes complete combustion giving a waste stream containing $CO_2$, water, inorganic pigments and traces of incompletely consumed paint binder. At higher flow rates of 100 ft per second the combustion of the paint binder material is seriously inhibited and the waste stream contains major amounts of potentially toxic partially consumed paint break down products.

The laser cleaning produces instantaneous combustion of the waste products and thus not only removes paint but also disposes of the removed paint by combustion. Concern with the appearance of a flame at the site of laser impingement led to further experimentation to determine if the flame was necessary and appropriate. Use of nitrogen removed all flame but immediately led to production of large quantities of tars and noxious fumes.

Increase of air flow rates to such high velocities that the flame appearance was extinguished gave similar results. An immediate great increase in noxious fume production was observed. It is apparent that flame control or elimination by increase in air flow rates will introduce a serious problem of greatly increased production of noxious and toxic by-products.

It is obvious that any full-scale laser cleaning will require further development of optimum air flow rates to insure maximum disposal of paint binder constituents by combustion at the point of removal. The total organic material removed and burned during laser cleaning with a full-scale 2-KW system will be substantially less than that consumed in the same time period by the average family car. Further monitoring of off-gas emmisions will be required to insure total compliance with OSHA and EPA standards. It is recommended that continuous monitoring of waste gas steam components be established as soon as a full scale high power laser cleaning system is built. Final resolution of concerns about waste stream composition and control awaits such measurements as will be available only from a fully operational system.

## 10.0 TEMPERATURE RISE

### 10.1 Tests Performed

Tests were made to determine the level of temperature rise experienced by a substratum material on exposure to laser paint removal by a pulsed laser.

In all experiments conducted under the standard operating conditions defined in Paragraph 3.4, we have been unable to detect any rise in temperature during depainting with the pulsed laser. The methods which are found to best demonstrate any surface temperature effects were repeated to verify the results on the higher power version of the system and to develop control data for number of sequential pulses allowable for commercial system design.

a. Various devices including thermal sensitive strips were subjected to laser pulses to attempt to detect any thermal effects on the substratum.

b. Paper impregnated with fluids of varying flash point were subjected to laser pulses to determine which if any would be raised to the point of sustained combustion by the pulsed laser energy.

c. Thin film thermocouple devices were subjected to laser energy pulses to determine if any transient surface temperature effects could be observed.

d. Glass, plexiglas and other nonconductive materials were painted and subjected to laser cleaning to seek evidence of surface heating effects.

e. Sensitive proteins were subjected to laser pulses to seek evidence of surface heating effects.

For the high pulse rate to be expected in any commercially sized laser paint stripping equipment the build up of heat from repeated pulses of laser energy may introduce heat related problems with the substratum. The higher powered equipment 1.4.3 was utilized to measure the rate and extent of possible heat build up.

Heat build-up was determined by depainting while a thermocouple measured heat on the reverse side of the sample.

### 10.2 Testing Results

The temperature reached by a surface exposed to pulsed laser energy in the 5-20 J/sq cm range with a pulse duration of 25 microseconds was strongly dependent on the heat conductivity of the sample.

Conductive material such as 2-mil aluminum showed a maximum temperature of less then 180 degrees Fahrenheit when subjected to repeated pulses at a rate of 8 pulses per second.

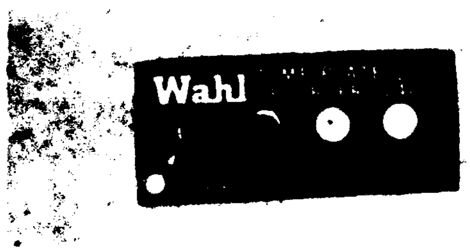
Single pulses of laser energy of 25 microseconds duration caused only very thin surface coagulation of liquid egg white.

Heat sensitive strips (Wahl Temp Plate Recorder #240), when exposed to single pulses of laser energy in the front (film protected) side, were unaffected. When exposed from the back side with the laser energy directly impinging on the heat sensitive material the spots which change color with temperature reacted as follows to a single pulse of laser energy of 1 microsecond duration at a fluence of 6 J/sqcm:

| | |
|---|---|
| 160 degrees F | turned black |
| 170 degrees F | turned black |
| 180 degrees F | partial change to grey |
| 190 degrees F | no change |

The heat sensitive strips were painted on the back side and then laser stripped with several pulses of laser energy of 1 microsecond duration at a fluence of 6 J/sqcm.

There was no change in the strips until sufficient paint was removed to partially expose the heat sensitive material. Then the results were the same as above. The conductivity of the paint was insufficient to change the nature of the observations.




Painted Side

Front Side

**Figure 10. Heat Sensitive Strips**

The accumulation of heat in a sample becomes more significant as higher powered lasers with more rapid pulse rates are utilized. Using the laser (1.4.3) the following heat build-up data were obtained.

| Material | Scanned Area | Fluence J/sqcm | Pulse rate /sec. | Time sec. | Max. Temp. degrees F |
|---|---|---|---|---|---|
| Al-0.032 | 1x6cm | 6 | 100 | 30 | 240 |
| Al-0.032 | 1x6cm | 6 | 100 | 5 | 200 |
| Al-0.032-Painted | 1x6cm | 6 | 100 | ~10 | 210 |
| Al-0.032 | 0.5x0.5cm | 6 | 100 | 3 | <230 |
| Al-0.032 | 0.5x0.5cm | 6 | 100 | 3 | >210 |

Continuous Scanning Experiments

The stationary beam experiments described above do not represent the conditions expected to be encountered in active practice of laser depainting. A closer approximation to practical use experience was developed. Temperatures were measured with a thermocouple attached to the back side of the sample as shown in Figure 11.

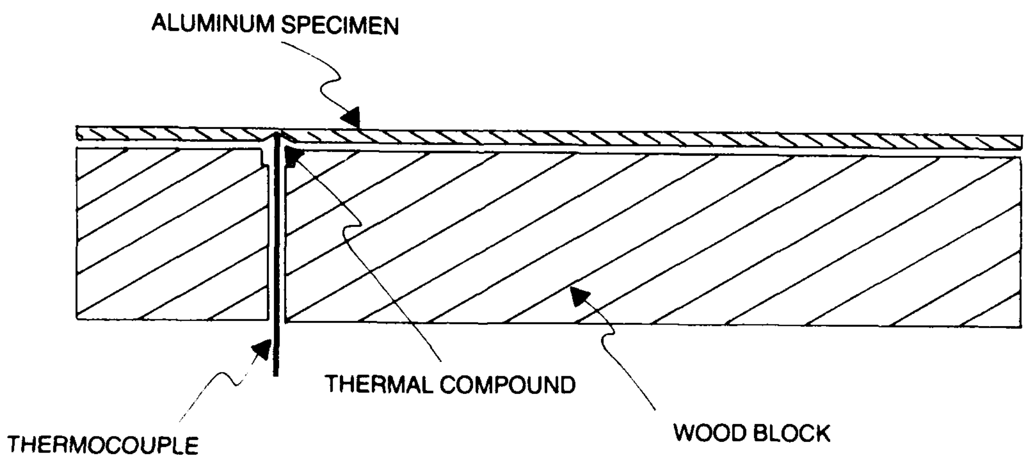



**Figure 11. Temperature Measurement Equipment**

The experiments were repeated using laser (1.4.3) with the beam delivery arm equipped with a beam distribution device so that each four sequential pulses of the laser energy were distributed in a line with approximately 10 percent overlap of the treated areas. This line was advanced across the sample to provide a continuous path of paint removal without the beam dwelling on any spot for longer than that period produced by the 10 percent pattern overlap. The aluminum samples were heated to varying starting temperatures in order to determine the residual heat imparted to a sample during a typical depainting operation in which repeated passes of the laser beam might be required to complete the removal of all paint.

The following tests were conducted using 0.016 aluminum 2024-T3, primed and painted on one side. All temperatures are degrees Fahrenheit.

| Starting Temp. | Maximum Temp. | Temp. Rise |
|---|---|---|
| 76 | 114 | 38 |
| 77 | 107 | 30 |
| 77 | 131 | 54 |
| 78 | 125 | 52 |
| 80 | 122 | 42 |
| 81 | 131 | 50 |
| 81 | 126 | 45 |
| 86 | 124 | 38 |
| 111 | 137 | 26 |
| 119 | 161 | 42 |
| 122 | 161 | 39 |
| 122 | 160 | 38 |
| 129 | 170 | 41 |
| 133 | 173 | 40 |
| 135 | 182 | 47 |
| 157 | 191 | 34 |
| 160 | 192 | 32 |

The heat rise problem may be different with anodized aluminum. The tests were repeated with 0.032 anodized 7075-T6.

| Starting Temp. | Maximum Temp. | Temp. Rise |
|---|---|---|
| 80 | 122 | 42 |
| 84 | 138 | 54 |
| 121 | 161 | 40 |
| 123 | 170 | 47 |
| 125 | 166 | 41 |

Anodized samples appeared warmer during depainting than the bare aluminum samples. Tests were conducted to determine the amount of reflected energy from various materials as an indication of potential for heat build-up during laser cleaning. Samples were mounted at a 45 degree angle to the incident laser beam and measurements taken of reflected energy.

| Material | Incident energy | Reflected Energy |
|---|---|---|
| Bare Aluminum 2024-T3 | 35 | 16 |
| Anodized Al 2024-T3 | 35 | 4 |

| Material | Incident energy | Reflected Energy |
|---|---|---|
| Alodined Al | 35 | 15 |
| Titanium | 62 | 45 |
| Composite graphite-epoxy | 62 | 1 |

The measurements of reflected energy do not fully represent all reflected energy but merely that reflected as a reasonably coherent beam. In the case of anodized material the light scattering from the surface is such that the total reflected energy exceeds that captured in the measuring device. The heat build-up tests however confirm that more heat is retained by anodized material than by bare aluminum. The graphite-epoxy sample represents a typical painted surface from which very little energy is reflected. The heating problem may be most serious on such materials and tests were run to measure the heat build-up at various depths on the samples.

All the following results represent tests on material NF-010.

Fluence was 12 J/sqcm in all cases.

Laser beam exposure was in a continuous scanning mode with repeated scanning sufficient to remove 2 mils of paint and expose primer from a 2 sq in area within 10-15 seconds.

Starting temperature of sample was 80 degrees F. in all cases.

Temperatures were measured at back side of, at 50 percent through the sample, and under the first ply of the sample. Measurements were made both in the center of the treated area and at a distance of one-half inch away from the treated area. The temperatures within the samples were measured at the bottom of holes 0.116 in dia. drilled from the back side of the sample.

Temperature rise on stripping composites

| Sample | Measurement Depth | Measurement Point | Maximum Temperature | Time to Reach Maximum (Sec.) |
|---|---|---|---|---|
| 1 | back | 1/2 in. | 91 F. | 90 |
| 2 | back | center | 141 F. | 90 |
| 3 | back | 1/2 in. | 99 F. | 90 |
| 4 | back | center | 123 F. | 90 |
| 5 | 50 % | 1/2 in. | 86 F. | 60 |
| 6 | 50 % | center | 153 F. | 60 |
| 7 | 50 % | 1/2 in. | 87 F. | 90 |
| 8 | 50 % | center | 137 F. | 90 |
| 9 | one ply | 1/2 in. | 92 F. | 90 |
| 10 | one ply | center | 182 F. | 45 |
| 11 | one ply | 1/2 in. | 94 F. | 120 |
| 12 | one ply | center | 218 F. | 40 |
| 13 | one ply | center | 166 F. | 45 |

### 10.3 Conclusions

Heat sensitive strips when exposed to single pulses of laser energy in the front (film protected) side were unaffected. When exposed from the back side with the laser energy directly impinging on the heat sensitive material the spots which change color with temperature showed that the temperature reached was less than 190 degrees Fahrenheit with a single pulse.

Sustained pulses at a rate of 100 pulses per second with an energy concentration of 7 J/sq cm and a pulse duration of 16 microseconds resulted in a maximum temperature of 200 degrees F on the reverse side of the aluminum sample of thickness 0.032 in.

With high pulse rate (100/sec) equipment the heat build up on the reverse side of a 0.032 anodized aluminum sample did not exceed 150 degrees F with 500 pulses of 5 J/sqcm. In practice the beam delivery equipment should be and can readily be so designed as to insure that no single spot is subjected to more than 8-10 pulses per second in a prolonged exposure.

The heat build up in less thermally conductive graphite-epoxy composite materials is significantly greater than in the case of aluminum. However, maximum temperatures at the base of the first ply of a composite sample during total removal of paint did not exceed the recommended temperatures for the heat baking step of the original paint application.

Temperature rise is a function of many factors:

- Input energy per pulse
- Surface paint reflectivity
- Substratum reflectivity
- Substratum conductivity
- Substratum mass
- Pulse duration
- Pulse frequency

In practical applications the energy applied to a painted surface is largely adsorbed and utilized in paint decomposition resulting in very small temperature rise in the substratum. Once the paint film is largely removed a greater portion of the energy is directed to the substratum and the reflectivity, conductivity and mass of the substratum determine the temperature rise.

The data presented elsewhere in this report show a lack of physical damage to substratum, both aluminum and composites, with repeated cycles of cleaning at pulse rates of 8 pulses/sec. and energy concentrations of 5-20 J/sqcm.

## 11.0 ULTRASONIC DAMAGE

### 11.1 Tests Performed

Ultrasound has been commonly used for the inspection and qualification of composite materials. As preliminary experiments, those specimens which were subjected to laser depainting in the SBIR Phase I portion of this project were subjected to ultrasonic inspection to determine the degree to which such inspection can detect surface damage to the composite structure. A portion of the Phase I samples represent overtreatment in which surface damage was readily detectable by microscopic examination. If ultrasonic inspection could show a difference in properties from background on such samples, it would constitute a method of continuous quality assurance which can be uniformly applied to laser paint removal systems.

Several samples being depainted with laser energy were equipped with acoustic wave detection devices to determine the extent to which acoustic waves are transmitted to and through samples during cleaning. Such devices were also examined for their potential as a continuous or real time control mechanism governing the cleaning process.

### 11.2 Testing Results

Investigation has not led to the identification of any instrument which shows any response to the small shock wave energy which may be transmitted through a sample. The literature contains discussion of shock wave produced by a pulse of 30 nanoseconds duration. Our work showed a loud pop with pulse duration of 1-2 microseconds but greatly reduced noise and no evidence of a shock wave effect at pulse durations of 10-30 microseconds.

While instrumentation did not measure the shock wave at the 1-2 microsecond pulse duration, this energy level lead to some damage to the samples. A set of samples which had below specification primer thickness showed significant delamination of paint from primer during depainting with a fluence of 8-10 J/sqcm and a pulse duration of 1-2 microseconds. The same conditions also produced loss of continuity of the anodized coating on anodized aluminum. Neither of these results could be reproduced on the same samples when depainted with a fluence of 7 J/sqcm and a pulse duration of 25 microseconds.

### 11.3 Conclusions

No detectable shock wave was transmitted through laser depainted samples. Indirect evidence of shock damage was obtained with laser depainting at pulse durations of below 2 microseconds. The 1-2 microsecond pulse which showed some evidence of shock wave damage as detected by the appearence of delamination of paint topcoat from thin primer also produced a very intense bang which obviously required ear protection.

The longer pulse of 20-30 microseconds gave none of the delamination effect and is much quieter as reported below. There appears to be no evidence of any shock wave problem with such equipment.

## 12.0 ELECTRONICS DAMAGE

### 12.1 Tests Performed

Measurement of electromagnetic pulse (EMP) effects and electrical noise generated during depainting.

Appropriate measurement equipment was located in proximity to the commercial version of the laser generating device and in proximity to samples being depainted to determine the effect if any on electrical equipment and integrated circuits.

Inability to observe any detectable level of electromagnetic pulse from the lasers described in Section 1.4.2 and 1.4.3 led to further experiments with more sensitive equipment. Paint was removed from a low cost portable radio receiver while it was in operation. Paint and printing was also removed from the micro chips located within this radio.

### 12.2 Testing Results

Measurement equipment located in proximity to the short pulse (1-2 microsecond) laser system 1.4.1 showed a moderate EMP effect with each laser pulse. This effect was insufficient to cause any problems with an Allen-Bradley programable controller (Model PLC4) located in the immediate vicinity.

Measurement equipment was unable to detect any EMP effect from the longer pulse (10-20 microsecond) laser system 1.4.2. This laser does not cause static on a nearby cheap portable battery operated radio. Removal of paint from the radio case and removal of identifying numbers on micro chips within the radio by use of pulsed laser energy caused no loss of function. Figure 12. A simple card type calculator was subjected to removal of a stripe of surface plastic with laser system 1.4.2. This treatment had no effect on functionality of the calculator.

The higher powered laser equipment (1.4.3) in the unprotected laboratory demonstration version does introduce moderate static into the local phone system and the static could be detected on a portable battery operated radio at 100 yards distance. No change in this static was detected during depainting operations and it is probable that the static was entirely produced by the unshielded power supply and pulse forming electronics of the laboratory version of the laser.

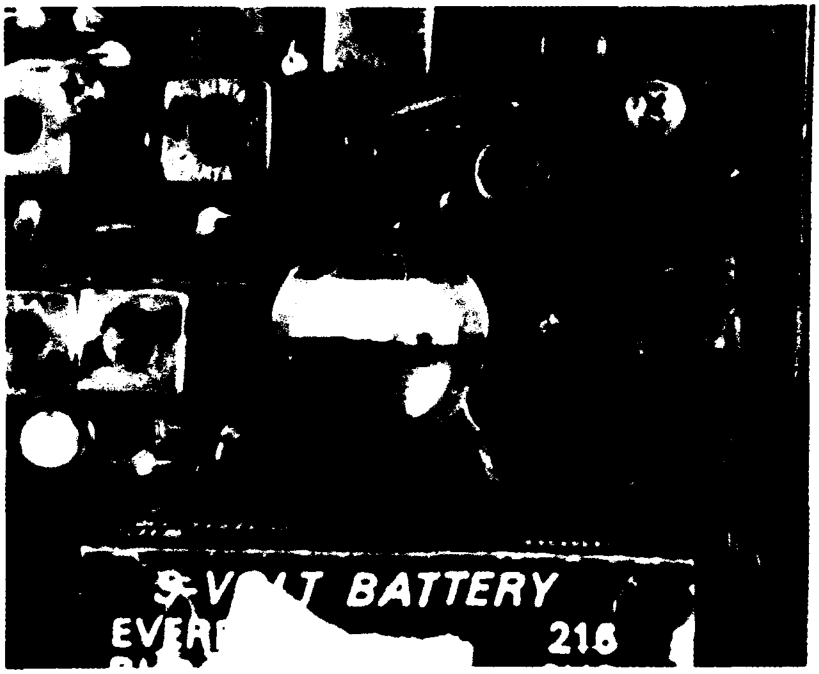



**Figure 12. Radio - Laser Cleaned**

### 12.3 Conclusions

We were unable to detect any EMP effect from laser system 1.4.2 and 1.4.3. Simple unprotected microchips were not disturbed.

System 1.4.3 with no protective devices did produce static on nearby phone and radio equipment. Field unit configuration will require appropriate shielding.

## 13.0 NOISE DETERMINATION

### 13.1 Tests Performed

Equipment was installed to measure the noise level produced by laser depainting and to determine the degree to which this noise can be attenuated by various simple shielding or noise suppression devices.

A meter, Quest - Model 208, was set at varying distances from the sample being depainted. Tests were conducted with pulsed lasers producing 10-20 microsecond pulses described in Sections 1.4.2 and 1.4.3.

### 13.2 Testing Results

Laser system 1.4.2 Fluence - 7 J/sqcm and 8 pulses/second.

| Distance from pulse | Decibels |
|---|---|
| 6 inches | 94 |
| 12 inches | 92 |
| 24 inches | 90 |
| 36 inches | 88 |
| 48 inches | 88 |
| 144 inches | 86 |

Laser system 1.4.3 Fluence - 5 J/sqcm and 100 pulses/second.

| Distance from pulse | Decibels |
|---|---|
| 6 inches | 88 |
| 12 inches | 86 |
| 24 inches | 84 |
| 36 inches | 78 |
| 72 inches | 72 |

### 13.3 Conclusions

Noise levels with use of a rapid pulse high energy laser do not exceed 90 decibels at 2-3 ft from the work surface. Use of ear protective devices is recommended.

## 14.0 METALLOGRAPHY AND FRACTOGRAPHY

### 14.1 Tests Performed

Damage to a composite surface when excessive laser treatment is applied could be readily observed under a microscope. No cross section examination was undertaken.

This technique was applied to selected samples of depainted anodized material to help explain the changes brought about by the laser depainting process.

### 14.2 Testing Results

The only areas deemed worthy of further study by microscopic examination were the anodized surfaces which underwent some unknown change not discernible by either conductivity or corrosion resistance measurements.

Samples were mounted and polished and microphotographs were made to attempt to identify any surface changes. See Figures 13-14.

Sample #02-002-0003

Magnification 2.2x

Top half of photo shows the stripped surface.

Bottom half of photo shows the unstripped surface.

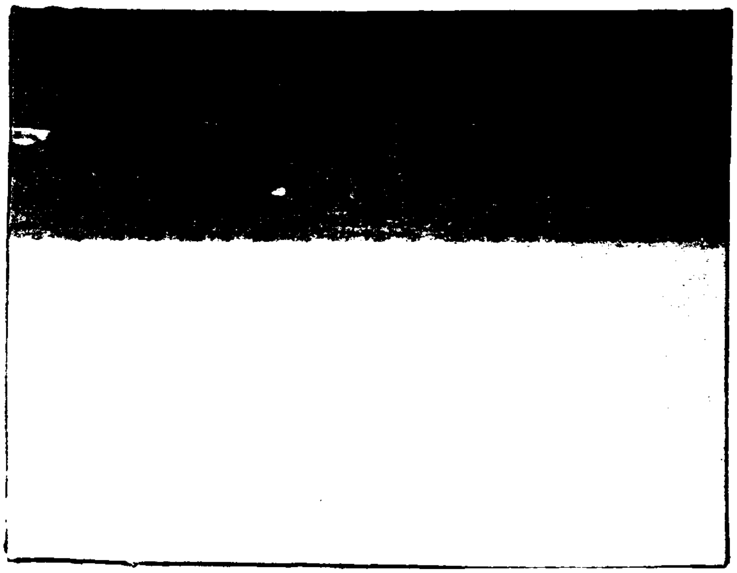


**Figure 13. Aluminum 2024-T3 bare anodized**

Sample #05-005-0004

Magnification 2.2x

Top half of photo shows the stripped surface.

Bottom half of photo shows the unstripped surface.

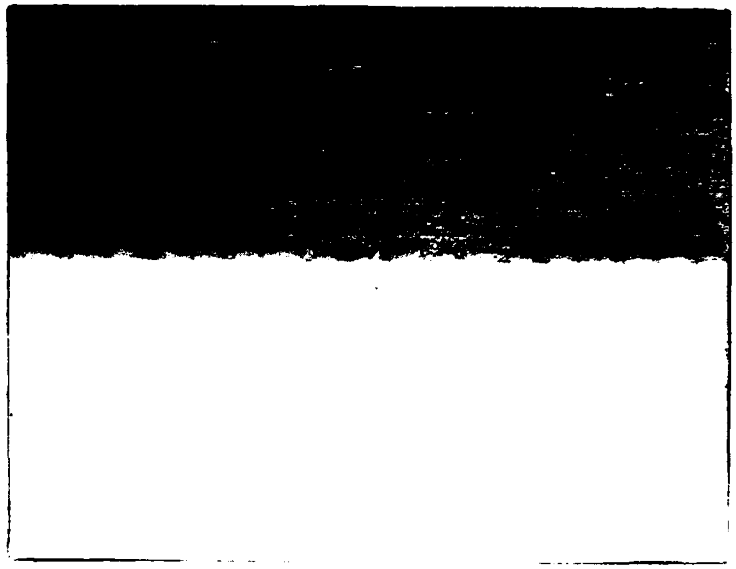


**Figure 14. Aluminum 7075-T6 bare anodized**

### 14.3 Conclusions

With the lack of detectable effects by other methodologies, only a few special samples were subjected to microphotography. Even in such cases no evidence of damage could be found.

## 15.0 QUALITATIVE CLEANING TESTS

### 15.1 Tests Performed

A series of samples supplied by the Air Force in a variety of shapes and ages of paint were subjected to laser depainting to gain comparative data as to the control problems present with cleaning of paint on various surfaces and configurations.

### 15.2 Testing Results

#### 15.2a Turbine Blades

A number of turbine blades supplied via the Air Force WPAFB were subjected to pulsed laser energy of 20 J/sqcm to test cleaning action. Systems 1.4.2 and 1.4.3 were utilized to remove all contamination.

The turbine blades were cleaned by hand held exposure to the pulsed laser. The surface material was readily removed leaving a clean smooth metallic surface. The first pass appeared to remove a more readily decomposable component from the surface. Repeated pases cleaned the blades with no evidence of any difficulty.

The cleaned blades were returned to the Air Force for evaluation. See Figures 15-16.

Turbine blade cleaning is a possible additional application of pulsed laser cleaning.

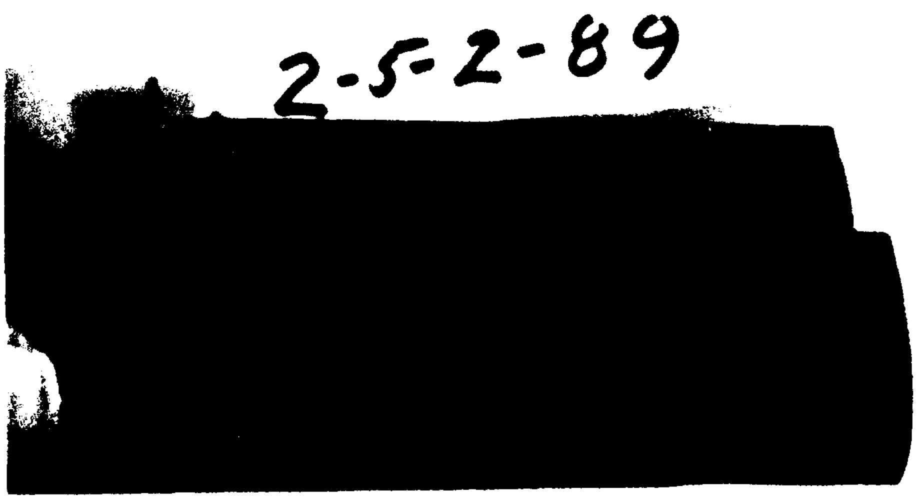



**Figure 15. Turbine Blade**

**Figure 16. Turbine Blade**

### 15.2b Nose Cone

A glass-epoxy composite nose cone 18 inches in diameter was painted with standard Air Force primer and top coat and then depainted to remove all paint leaving clean primer. See Figure 17.

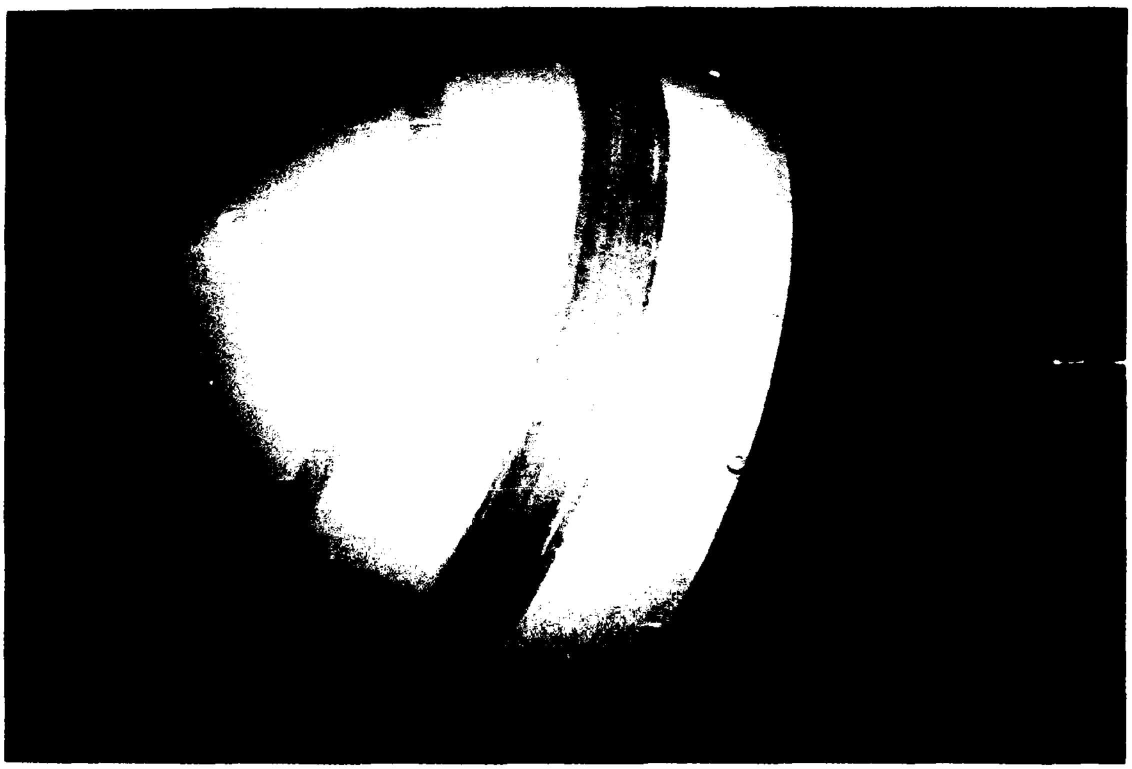


**Figure 17. Nose Cone**

### 15.2c Fasteners

An aluminum panel with a variety of typical aircraft fasteners was depainted to illustrate the ability of the laser to remove paint from fastener surface features. See Figure 18.

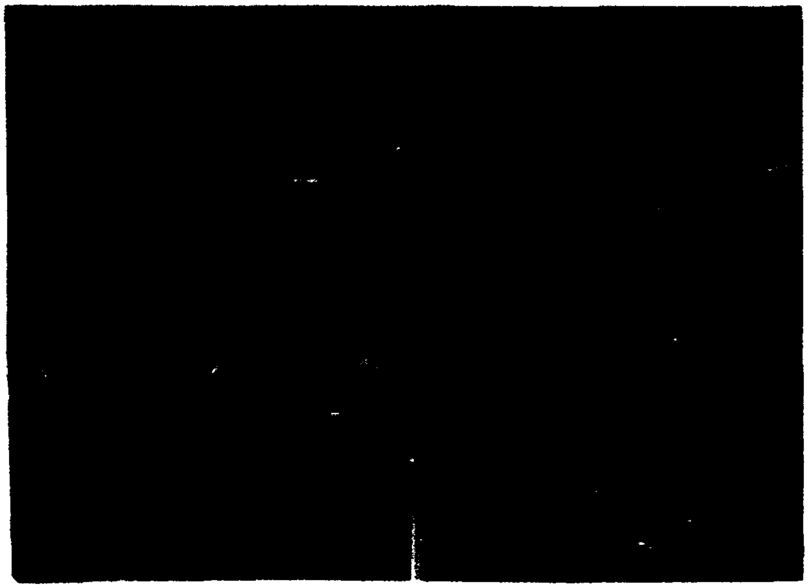


**Figure 18. Fastener Panel**

### 15.3 Conclusions

Complex shapes offered no problems which could not be solved by manual manipulation of the laser delivery head. Turbine blades, fastener heads and composite structures were successfully cleaned and/or depainted.

## 16.0 SPOT SIZE AND BEAM INTENSITY

### 16.1 Tests Performed

A series of experiments were carried out in which the sample was placed at varying distances from the laser in a divergent laser beam. Variations in standoff distance resulted in the fixed pulse energy being spread over a larger or smaller area. The fluence or beam intensity was therefore modified along with the projected spot size. This also permitted determination of the degree to which the depth of paint removal per laser pulse could be controlled.

Tests were also conducted to determine the degree to which the exposure of primer can be detected and measured during and between pulses. Such tests were accomplished visually and did not require use of color detection vision systems.

These experiments were extended to develop design data for the commercial application of the system to sensitive materials such as graphite/epoxy composites.

### 16.2 Testing Results

With very short pulses (1-2 microseconds) a potential problem in the area of paint adhesion was encountered. Samples depainted with short pulses showed a tendency for the final layer of paint to lose adhesion to the primer before being removed by a subsequent pulse of laser energy. This microscopically observable loss of adhesion could not be detected in samples depainted with the longer pulse (10-30 microsecond) equipment.

Samples of plexiglas and samples with extra heavy coats of paint were placed at varying distances from the laser in a divergent laser beam utilizing all three laser systems.

Plexiglas (non-pigmented acrylic)

| Pulse length (microseconds) | Joules/sqcm /pulse | Mg removed /joule |
|---|---|---|
| 2 | 30 | 0.13 |
| 2 | 25 | 0.14 |
| 2 | 20 | 0.13 |
| 2 | 16 | 0.16 |
| 2 | 13 | 0.15 |
| 2 | 11 | 0.13 |
| 2 | 10 | 0.13 |
| 2 | 9 | 0.09 |
| 2 | 8 | 0.07 |
| 2 | 7 | 0.03 |
| 2 | 6 | 0.01 |
| 25 | 23 | 0.26 |
| 25 | 17 | 0.26 |
| 25 | 11 | 0.20 |
| 25 | 6.6 | 0.10 |

Plexiglas (non-pigmented acrylic)

| Pulse length (microseconds) | Joules/sqcm /pulse | Mg removed /joule |
|---|---|---|
| 25 | 4.7 | 0.01 |
| 16 | 7.9 | 0.32 |
| 16 | 5.2 | 0.40 |
| 16 | 6.3 | 0.44 |
| 12 | 5.2 | 0.41 |
| 20 | 5.2 | 0.39 |
| 20 | 7.0 | 0.44 |
| 16 | 12.5 | 0.35 |
| 20 | 13.0 | 0.37 |
| 12 | 11.8 | 0.32 |

Urethane Paint removal

| Pulse length (microseconds) | Joules/sqcm /pulse | Mg removed /joule |
|---|---|---|
| 2 | 20 | 0.09 |
| 25 | 23 | 0.28 |
| 25 | 20 | 0.26 |
| 25 | 17 | 0.23 |
| 25 | 13 | 0.26 |
| 25 | 11 | 0.18 |
| 25 | 9.2 | 0.18 |
| 25 | 6.6 | 0.16 |
| 25 | 5.7 | 0.10 |
| 25 | 4.7 | 0.08 |
| 25 | 4.1 | 0.05 |
| 25 | 3.5 | 0.03 |

The data scatter is such that no significant difference in removal rates with pulse duration over the range 12 to 25 microseconds duration can be seen. With pulse energy densities below 8-10 J/sq cm significant loss of paint removal efficiency is observed.

Using laser systems 1.4.2 and 1.4.3, tests with paint over yellow primer showed ready visual identification of exposure of primer and easy visual control of the process such that primer could be left intact. See Figure 19.

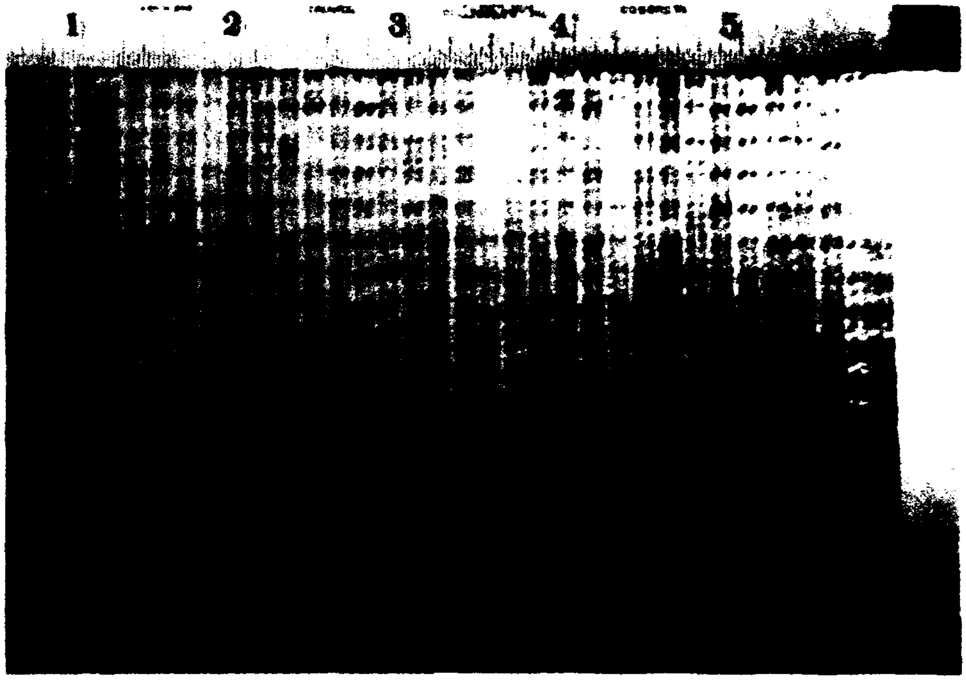



**Figure 19. Composite with retained primer**

### 16.3 Conclusions

Effective paint removal rates are obtained with fluence of greater than 6 J/sqcm per pulse. Below that level there is increasing evidence of soot formation and charring. At beam intensities of less than 3 J/sqcm serious paint charring occurs and might increase the risk of leaving residual carbon.

At increased fluence above 6 J/sqcm there is improved removal efficiency as measured by paint removed per Joule of energy supplied. It appears that optimum fluence range is 8-12 J/sqcm.

Small variation in removal rates was observed with the degree of pigment loading in different paints. This effect was much more pronounced in qualitative tests run on a very heavily loaded ship anti-foulant paint in which the high copper content produced reduction in removal rates through increased reflectivity of the laser energy. The laser depaint system should be specifically checked for optimum fluence efficiency with each paint system being stripped.

## 17.0 METAL MECHANICAL PROPERTIES - TENSILE

### 17.1 Tests Performed

Tension: I.A.W. ASTM E8

Tests were conducted in an environmentally controlled laboratory. The strain rate to be 0.005 inch per minute, as indicated by a strain pacer, until the yield strength is exceeded, then increased to 0.1 inch per minute to failure. The tensile yield strength at 0.2 percent offset, the tensile ultimate strength, the elongation and the tensile modulus of elasticity were obtained.

Materials:

Aluminum alloy 2024-T3 bare

Material thickness: 0.032 inches

Number of samples:

Ten samples of the material were tested in as-received condition to establish base line for comparison.

Ten samples of the material were tested after four cycles of laser depainting to an extent which insured removal of all surface paint and approximately 50 percent of the primer followed by repriming and repainting. The final depainting removed all paint to bare metal and the tests were run on such fully depainted samples.

This test was considered for application after each stage of cleaning but the total cost of the very large number of samples to be prepared and tested required rethinking as to the need for such testing. LTI has concluded that the performed tests will validate the technology and that intermediate tests with fewer cycles of cleaning would add no significant knowledge.

Specimen Preparation, Cleaning and Repaint Procedures: See Section 3.3.

### 17.2 Testing Results

Aluminum alloy 2024-T3 bare

Samples depainted with laser system 1.4.2 using 8 pulses per second of 25 microseconds duration with energy density on sample of 20 J/sq cm.

| Sample No. | Depainting cycles | Tensile Strength at Yield (psi) | Tensile Strength at Break (psi) | Elongation (%) |
|---|---|---|---|---|
| 01-006-0014 | Control | 64960 | 63590 | 16.3 |
| 01-006-0015 | Control | 64750 | 64400 | 16.7 |
| 01-009-0013 | Control | 65470 | 64390 | 17.0 |
| 01-009-0014 | Control | 65109 | 63520 | 16.4 |
| 01-009-0015 | Control | 65070 | 65030 | 11.6 |
| Average | | 65088 | 64186 | 16.6 |
| 01-006-0009 | 4 | 66980 | 65260 | 15.6 |
| 01-006-0010 | 4 | 65060 | 63450 | 16.1 |
| 01-006-0013 | 4 | 64790 | 62990 | 17.1 |
| 01-009-0010 | 4 | 67330 | 65580 | 16.3 |
| 01-009-0012 | 4 | 65250 | 64210 | 18.6 |
| 01-006-0011 | 4 | 64660 | 63360 | 16.3 |
| 01-006-0012 | 4 | 64540 | 63290 | 15.5 |
| 01-007-0007 | 4 | 66570 | 64480 | 16.2 |
| 01-009-0009 | 4 | 67080 | 65560 | 16.2 |
| 01-009-0011 | 4 | 67330 | 65580 | 16.0 |
| Average | | 65959 | 64403 | 16.39 |

## 17.3 Conclusions

Aluminum alloy 2024-T3 bare.

There was no evidence of change of any tensile strength properties after four cycles of laser depainting and repainting.

## 18.0 METAL MECHANICAL PROPERTIES - FATIQUE CRACK GROWTH

### 18.1 Tests Performed

Laser depainted samples were tested in accordance with ASTM Method E647.

Materials: Aluminum alloy 2024-T3 bare.

Material thickness: 0.016 inches

Ten samples were tested in as received condition.

Ten samples were depainted and repainted through four cycles with laser system 1.4.3 using 100 pulses per second of 20 microseconds duration with energy density on sample of 20 J/sq cm. On the forth cycle the samples were laser depainted to completely remove all paint and then tested without repainting.

Specimen Preparation and Cleaning Procedures: See Section 3.3.

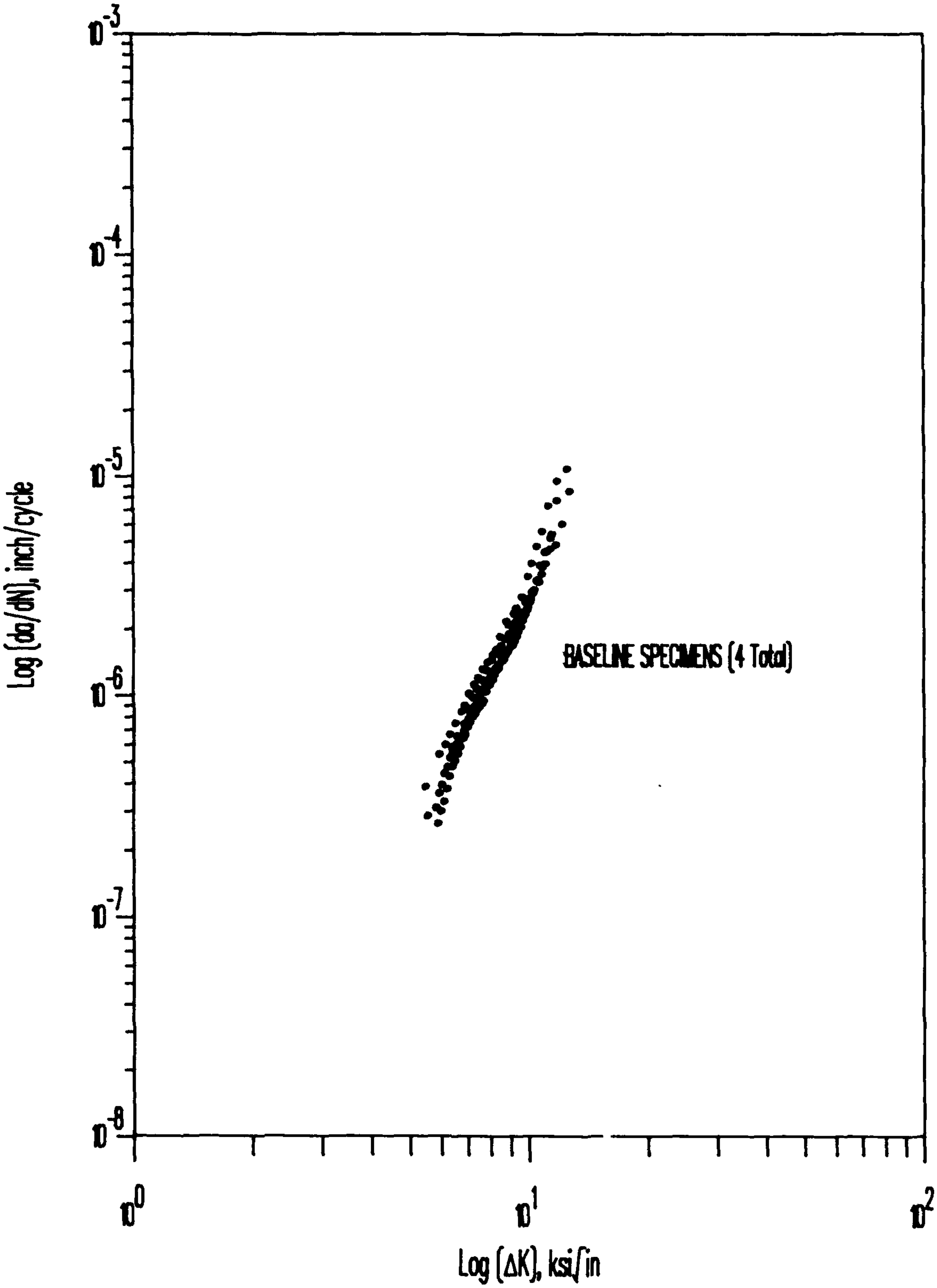
### 18.2 Testing Results

Aluminum alloy 2024-T3 bare, 0.016.

Specimens were machine finished to final dimensions. A 1/8 inch diameter starter hole was drilled through the center of the specimen. The 0.040 inch starter notch was machined by electrical discharge machining using a 0.006 inch traveling wire cut, thereby producing a notch width less than 0.010 inch wide. All specimens were fabricated with sheet rolling direction parallel to the applied load and perpendicular to the notch direction.

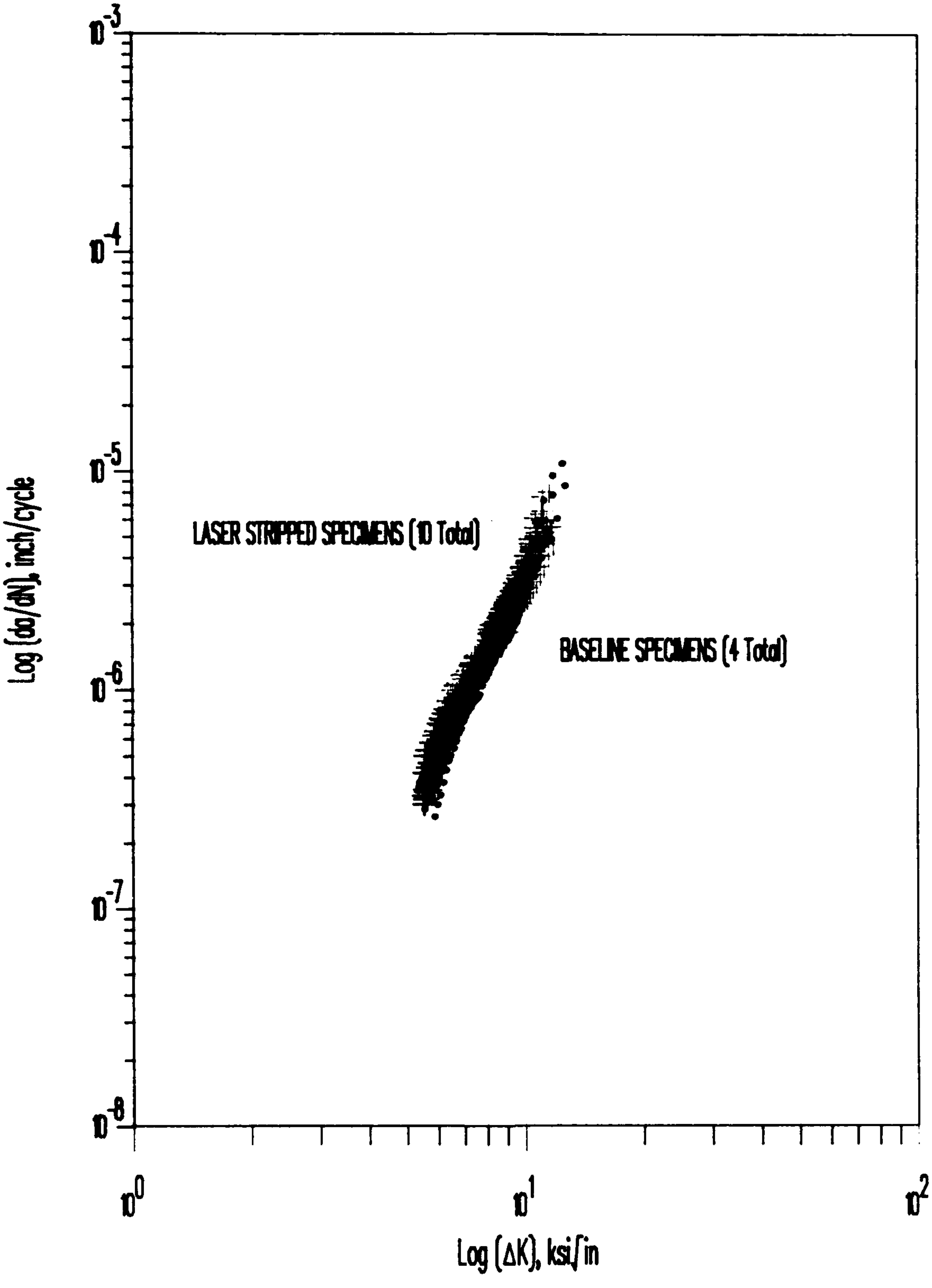
Specimens were cycled under load control with sinusoidal waveform at 30 Hertz. Test loads were constant amplitude with a +0.1 stress ratio and a maximum load of 270 pounds. The nominal maximum stress for these tests was 6,250 psi. Crack growth measurments were made with cast epoxy KraK Gages.

Data is presented in Figures 20 through 25. The figures are log-log plots of crack growth per load cycle as a function of the change of the stress intensity factor experienced at the crack tip.



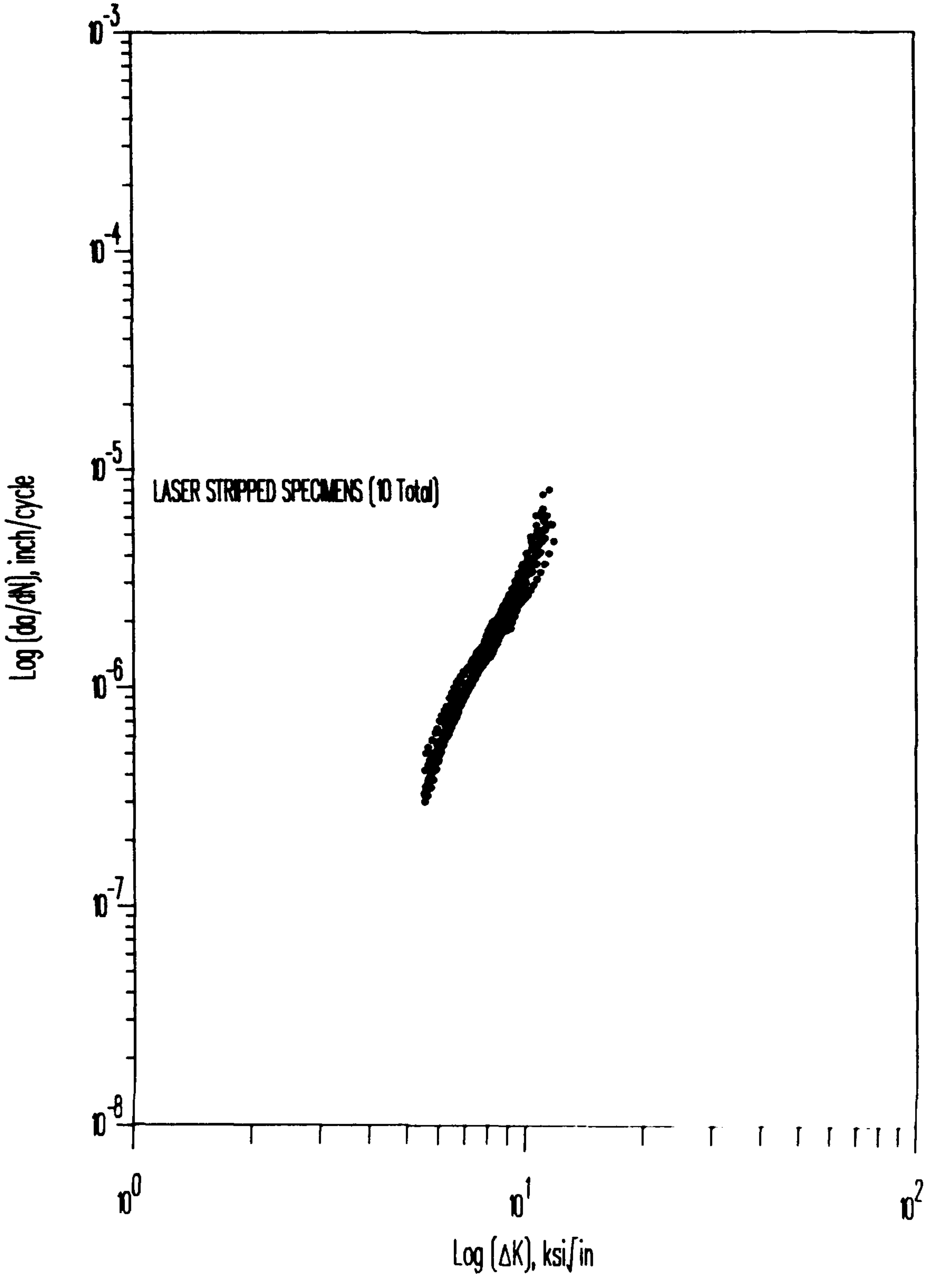

FCG DATA FOR BASELINE SPECIMENS

**Figure 20.**



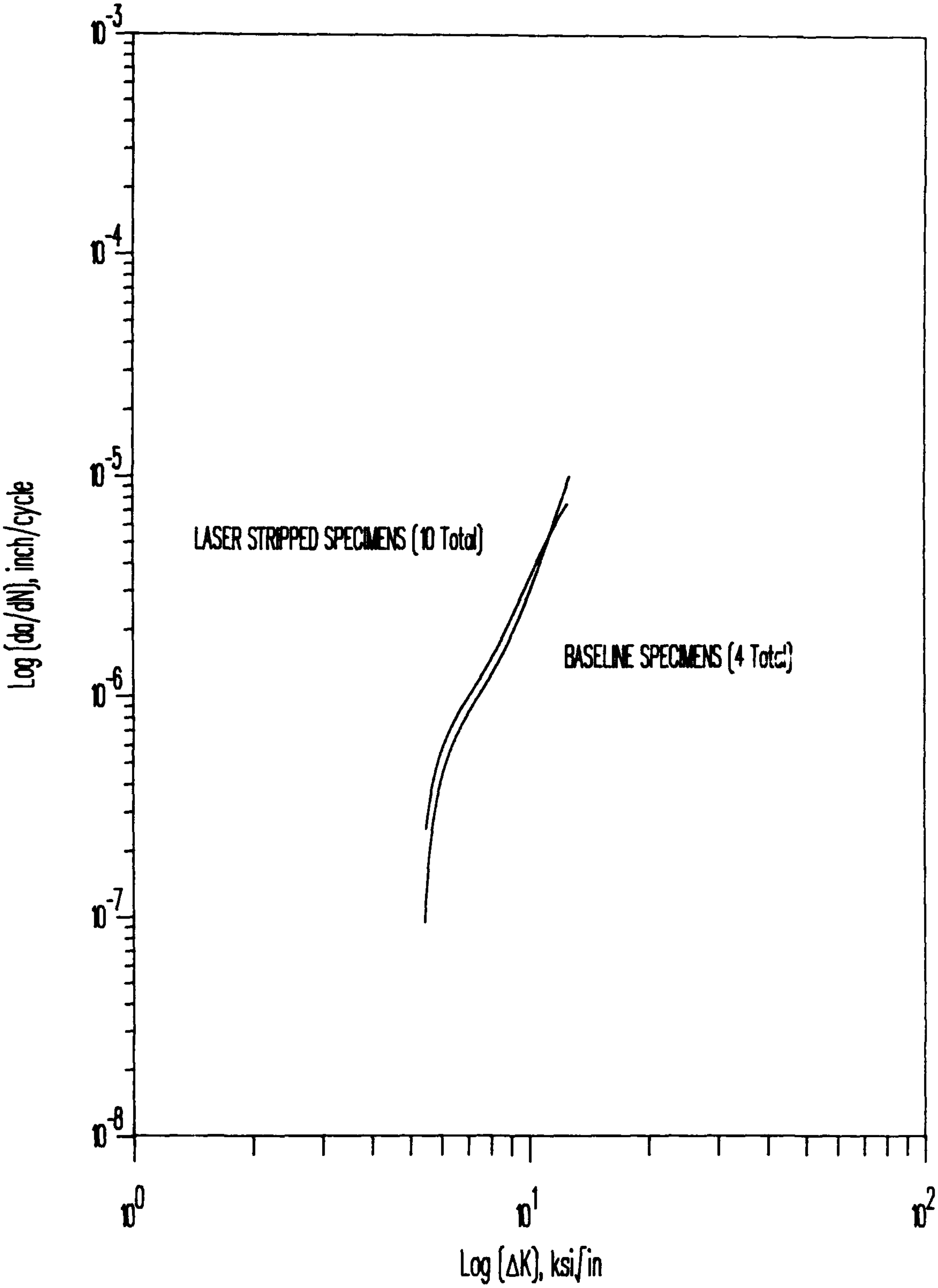

FCG DATA FOR BASELINE AND EXPERIMENTAL SPECIMENS

**Figure 21.**



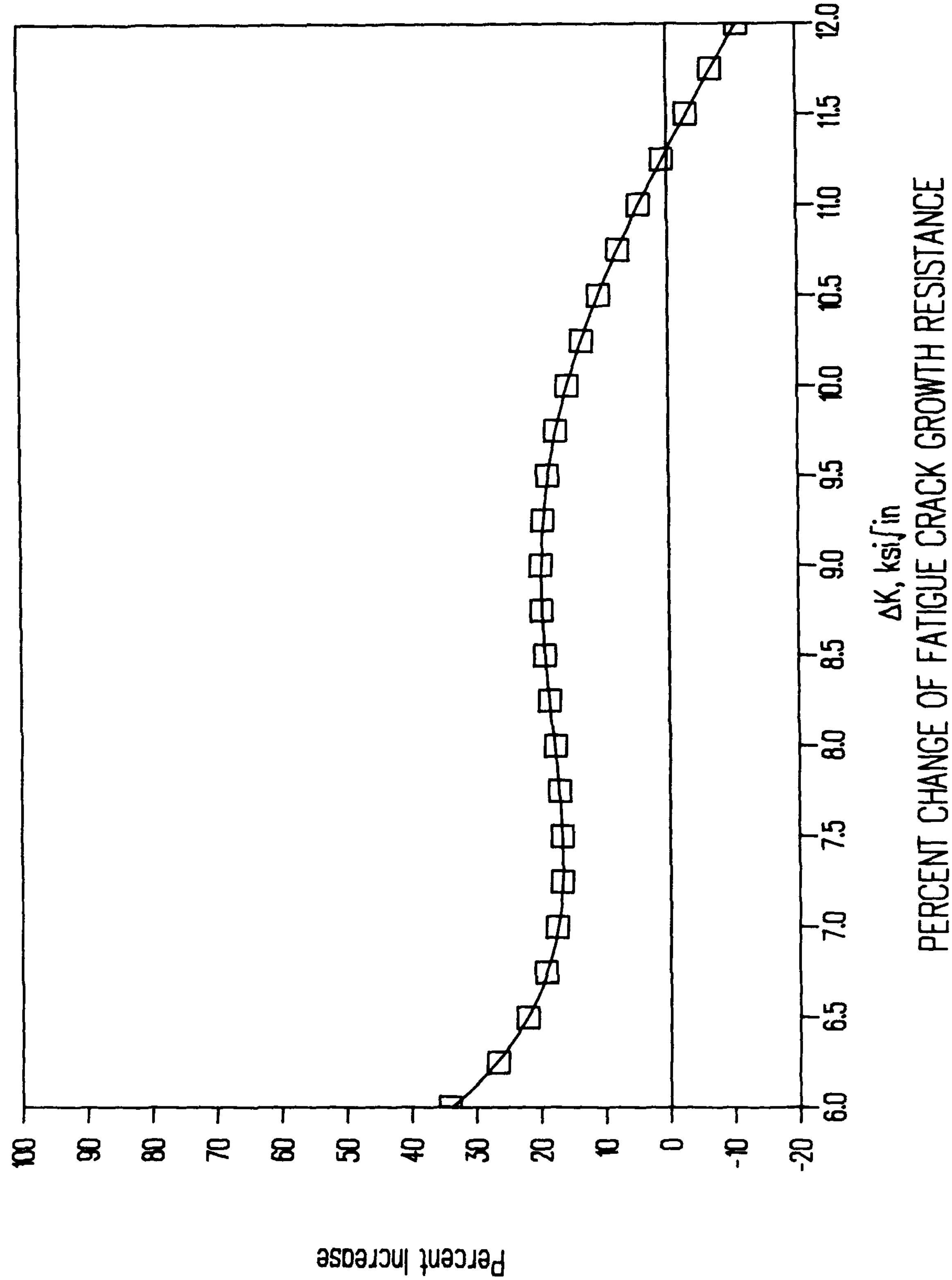

FCG DATA FOR LASER STRIPPED SPECIMENS

**Figure 22.**



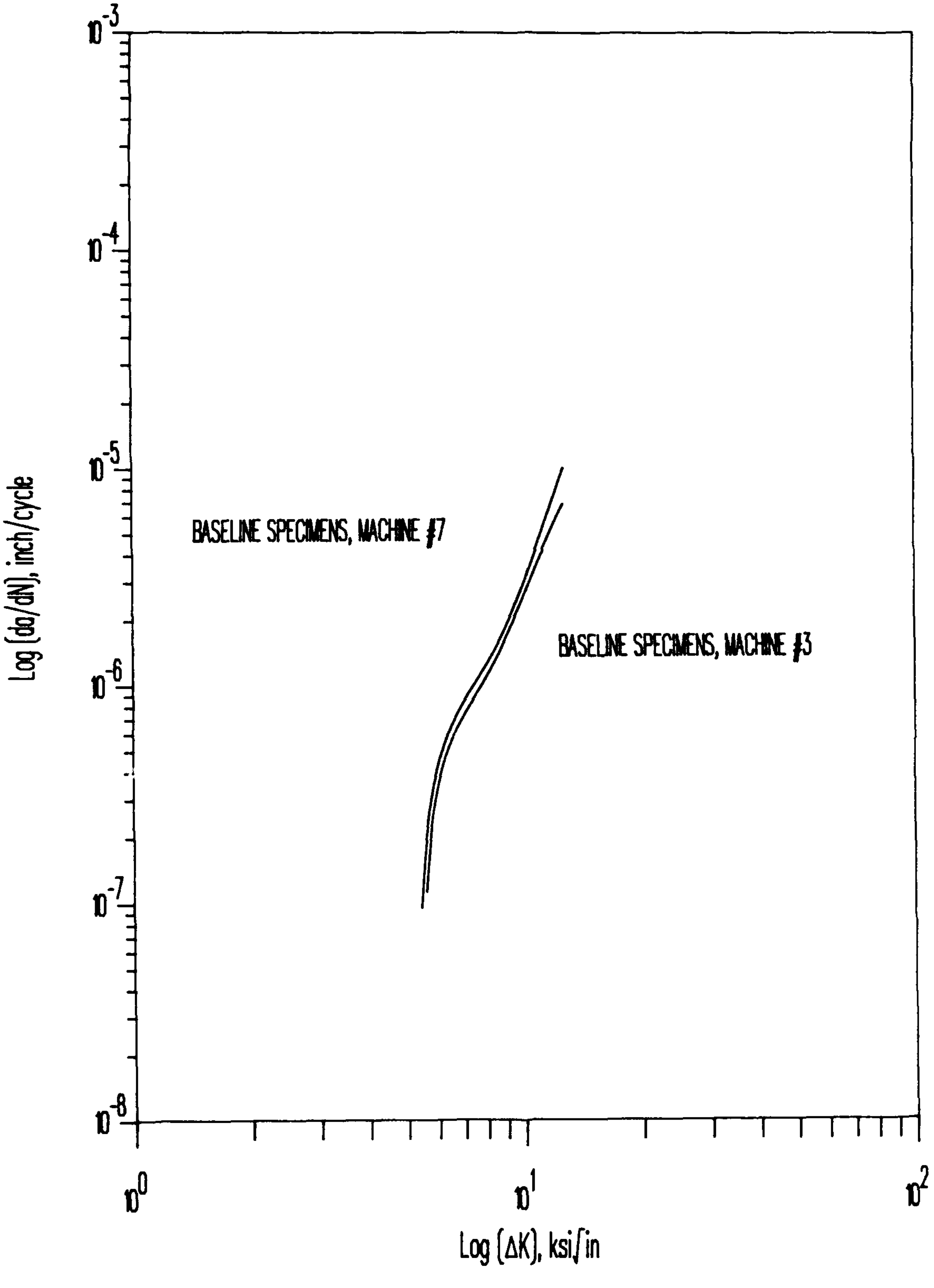
CURVE FIT COMPARISON OF FCG DATA

**Figure 23.**



PERCENT CHANGE OF FATIGUE CRACK GROWTH RESISTANCE
ΔK, ksi√in
Percent Increase
6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5 10.0 10.5 11.0 11.5 12.0
100 90 80 70 60 50 40 30 20 10 0 -10 -20


**Figure 24.**




BASELINE FATIGUE CRACK GROWTH, MACHINE DIFFERENCES

**Figure 25.**

## 18.3 Conclusions

Aluminum alloy 2024-T3 bare, 0.016.

No evidence was found of change of any crack growth properties after four cycles of laser depainting and repainting using energy densities in excess of those required for paint removal.

## 19.0 METAL MECHANICAL PROPERTIES - RESIDUAL STRESS

### 19.1 Tests Performed

Almen Strips: I.A.W. MIL-S-13165B

Almen strips mounted in holding blocks were subjected to 5, 10, 15 and 20 pulses of laser depainting energy. Arc height was measured after each 5 pulses.

Tests were redesigned to increase sensitivity as follows.

Strips 12 inches in length were mounted in a clamp holding only the lower 1 inch with the balance rising vertically from the clamp. The painted strips were subjected to pulsed laser energy far in excess of that required to remove paint over an area of 1 inch vertical heigth of the strip and at a location 1 inch above the holding clamp. Deflection of the upper end of the strip was determined during the laser treatment. See Figure 26.

Materials:
- Aluminum alloy 7075-T6 bare.
- Material thickness: 0.032 inches
- Specimen Preparation Procedures: See Section 3.3.

### 19.2 Testing Results

Almen Strips: I.A.W. MIL-S-13165B
No detectable effect.

Redesigned test:

| Sample No | Number Pulses | Fluence | Deflection |
|---|---|---|---|
| 04-006-0008 | 250 | 23 J/sqcm | <.001 |
| 04-006-0008 | 250 | 20 J/sqcm | <.001 |
| 04-006-0008 | 300 | 20 J/sqcm | <.001 |

### 19.3 Conclusions

Almen Strips: I.A.W. MIL-S-13165B
No detectable effect.

Redesigned test:
Aluminum alloy 7075-T6 bare

No detectable deformation <0.001 inches.

The standard Almen test gave no observable deformation. A redesigned test to give the greater sensitivity of single point mounting and longer free arm to increase level of detectable bending failed to disclose any deformation during laser depainting. As expected the laser interaction produces no discernable compressive forces on the surface being depainted. "Photon" loading and acoustic loading are insignificant factors at the fluence levels and pulse lengths used during depainting.

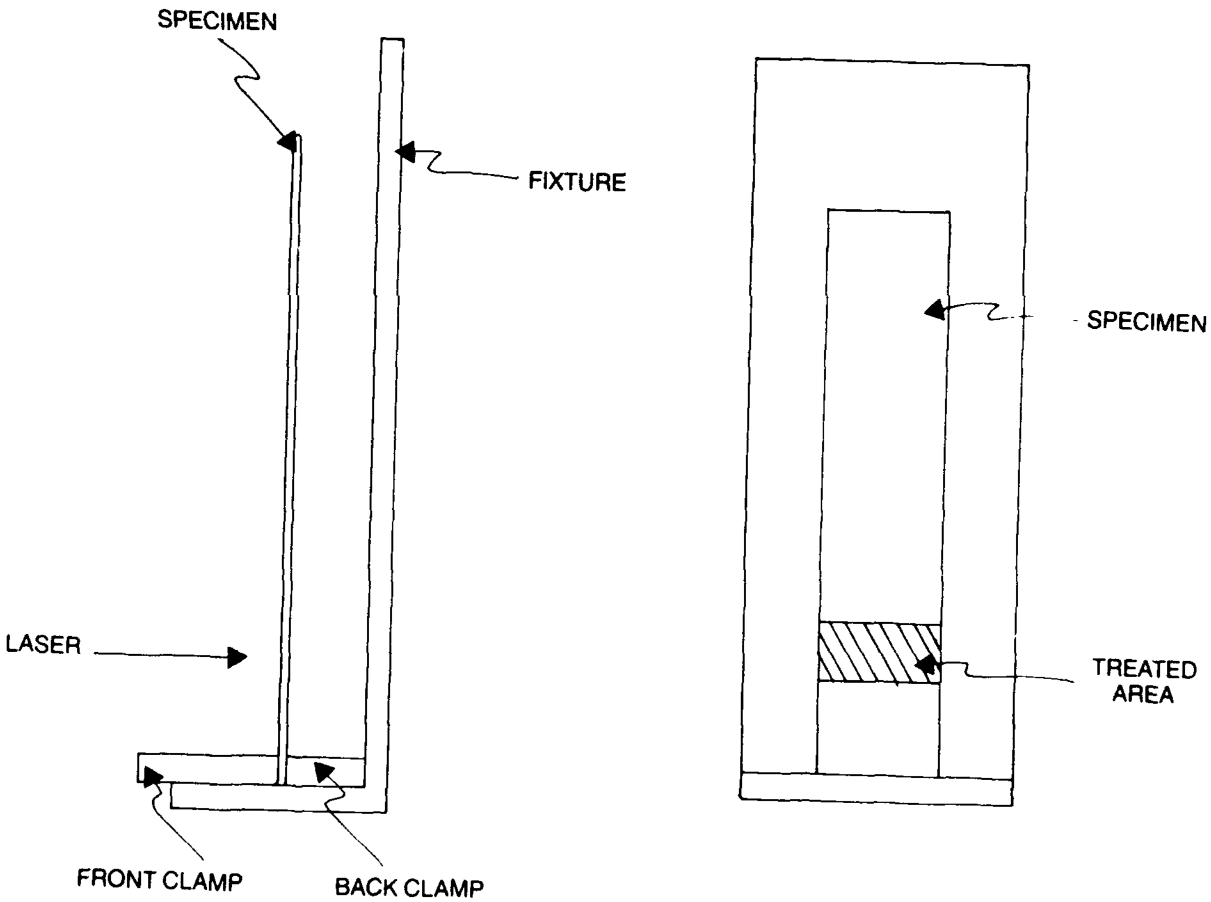



**Figure 26 - Residual stress test stand**

## 20.0 COMPOSITE MECHANICAL PROPERTIES - TENSILE

### 20.1 Tests Performed

Tests were conducted to determine Tensile Strength and Modulus: I.A.W. ASTM D3039 (perpendicular to fiber direction)

A 10,000 lbs capacity Instron testing machine, crosshead speed 0.05 inch/minute was used. Tensile strain was obtained using a 2 inch clip-on type extensometer.

Material: 16 ply Unidirectional IM6/3501-6 Graphite/epoxy composite

Five samples perpendicular to surface fiber direction were tested, in as-received and another five after four cycles of laser depainting and repainting. Depainting in each case proceeded to the point where approximately 10 percent of the primer layer was removed. Repainting was done without renewal of primer.

The removal procedure was visually controlled through observation of the appearance of the underlying primer as the paint was removed. This was easily accomplished and substantial amounts of primer remained after the fourth cycle of depainting.

### 20.2 Testing Results

Tensile Strength and Modulus: I.A.W. ASTM D3039 (perpendicular to fiber direction)
Unidirectional Graphite/epoxy composite

Samples depainted with laser system 1.4.2 using 8 pulses per second of 25 microseconds duration with energy density on sample of 20 J/sq cm.

| | Depainting cycles | Tensile Strength Maximum (psi) | Elongation Ultimate (%) | Modulus (psi) |
|---|---|---|---|---|
| | none | 3673 | .5808 | 807900 |
| | none | 4599 | .8028 | 681300 |
| | none | 3597 | .5571 | 706100 |
| | none | 3044 | .4006 | 763600 |
| | none | 4735 | .5645 | 855800 |
| Mean: | | 3929 | .5812 | 762900 |
| | four | 3590 | .4913 | 734600 |
| | four | 3443 | .6638 | 530600 |
| | four | 3565 | .7102 | 511100 |
| | four | 3341 | .4727 | 715000 |
| | four | 4256 | .6562 | 694100 |
| Mean: | | 3639 | .5989 | 637100 |

### 20.3 Conclusions

Tensile Strength and Modulus: I.A.W. ASTM D3039 (perpendicular to fiber direction)

The tensile tests showed a small decrease on tensile strength of the five samples tested. The data scatter for the laser depainted samples was narrower than for the control samples and all measurements were within the expected scatter range for this type of material when measured in the matrix dominated direction. The tests perpendicular to fiber direction in the unidirectional composite were selected as most sensitive indicators of damage.

The test indicates that laser depainting did no major damage. The visual control of the depainting process was adequate to retain primer even with the use of higher than required fluence. The tests would require repetition with a much larger number of samples to establish on a statistical basis the presence or absence of a small degree of damage.

## 21.0 COMPOSITE MECHANICAL PROPERTIES - FLEXURAL

### 21.1 Tests Performed

Flexural Properties Tests: I.A.W. ASTM D790-84a, Method II (four point flexure).

A 10,000 lbs capacity Instron testing machine, with load fixture adjusted to give 2.0+ inches with span to depth ratio of 32:1 was used. The mid-span deflection was determined with deflectometer having a microformer for an electrical output.

Material: 16 ply Unidirectional IM6/3501-6 Graphite/epoxy composite

Ten samples were tested, in as-received and after four cycles of depainting and repainting. Depainting in each case proceeded to the point where approximately 10 percent of the primer layer was removed. Repainting was done without renewal of primer.

Specimen Preparation and Cleaning and Repaint Procedures: See Section 3.3.

### 21.2 Testing Results

Flexural Properties Tests: I.A.W. ASTM D790-84a, Method II (four point flexure)

Samples depainted with laser system 1.4.2 using 8 pulses per second of 25 microseconds duration with energy density on sample of 20 J/sqcm.

| | Cleaning cycles | Load at Yield (lbs) | Tangent Modulus (psi) | Flexural Strength (psi) |
|---|---|---|---|---|
| | none | 35.69 | 893000 | 5968 |
| | none | 24.26 | 879200 | 5042 |
| | none | 30.10 | 940200 | 5236 |
| | none | 25.46 | 947800 | 5772 |
| | none | 33.34 | 1139000 | 7345 |
| Mean: | | 29.77 | 959900 | 5872 |
| | four | 22.95 | 806200 | 3822 |
| | four | 35.99 | 1022000 | 6378 |
| | four | 29.52 | 947600 | 5710 |
| | four | 49.85 | 1010000 | 7947 |
| | four | 32.24 | 934300 | 6782 |
| Mean: | | 34.11 | 943900 | 6128 |

## 21.3 Conclusions

Flexural Properties Tests: I.A.W. ASTM D790-84a, Method II (four point flexure).

The flexural tests showed a small but statistically significant increase in strength of the five samples tested. However, the laser cleaned samples retained some primer in contrast to the base line samples which were tested in as received condition with no primer or paint. The residual primer, which was left on the laser depainted samples in order to insure minimum laser action on the structural material, appears to contribute to the measured properties.

The test indicates that laser depainting did no damage.

## 22.0 COMPOSITE MECHANICAL PROPERTIES - COMPRESSION

### 22.1 Tests Performed

Tests were conducted to determine the laser depainting effects on composite materials compressive strength. Test: I.A.W. ASTM D695

Material: 16 ply Unidirectional IM6/3501-6 Graphite/epoxy composite

Twelve samples were tested, in as-received and after four cycles of laser depainting and repainting. Depainting, in each case, proceeded to the point where approximately 10 percent of the primer layer was removed. Repainting was done without renewal of primer.

Specimen Preparation and Cleaning and Repaint Procedures: See Section 3.3.

### 22.2 Testing Results

Samples were depainted with laser system 1.4.2 using 8 pulses per second of 25 microseconds duration with energy density on sample of 20 J/sq cm.

| | Cleaning cycles | Compressive Strength (psi) | Compressive Modulus (psi) | Maximum Load lbs |
|---|---|---|---|---|
| | none | 49660 | 7165000 | 2404 |
| | none | 57120 | 7488000 | 2759 |
| | none | 63190 | 7319000 | 3286 |
| | none | 41770 | 7500000 | 1908 |
| | none | 56380 | 7034000 | 2705 |
| Mean: | | 53620 | 7301000 | 2612 |
| | four | 78800 | 8743000 | 3654 |
| | four | 64320 | 8266000 | 3248 |
| | four | 60030 | 8165000 | 2808 |
| | four | 36440 | 5388000 | 1811 |
| | four | 79680 | 8424000 | 4032 |
| Mean: | | 63850 | 7797000 | 3111 |

### 22.3 Conclusions

The compression tests showed a small but statistically significant increase in strength of the five samples tested. As with the flexural tests this can be attributed to the presence of residual primer on the laser depainted samples.

The test indicates that laser depainting did no damage.

## 23.0 RESIDUAL CARBON

### 23.1 Tests Performed

Previous depainting studies with lasers had resulted in the fear that a carbon residue may be left on the work piece and might cause future corrosion. In this investigation all possible carbon formation situations were observed and attempts were made to collect and analyze any suspect material.

The presence of carbon was strongly suspected in those cases in which very low fluence gave what appeared to be charring of the paint film. At practical operating levels of 8 to 10 J/sq cm or more no such charring was observed and no material for analysis could be collected.

### 23.1B Corrosion tests for residual carbon.

After repeated failure to identify any carbon residue a test was devised to maximize the opportunity for carbon, if formed, to show an influence on corrosion. Test samples were prepared by fastening together two painted samples and then laser depainting the joint area including depainting at an angle to give maximum removal of paint within the joint. Samples were depainted, repainted and subjected to salt spray corrosion test according to procedure 4.1.2. See Figure 27.

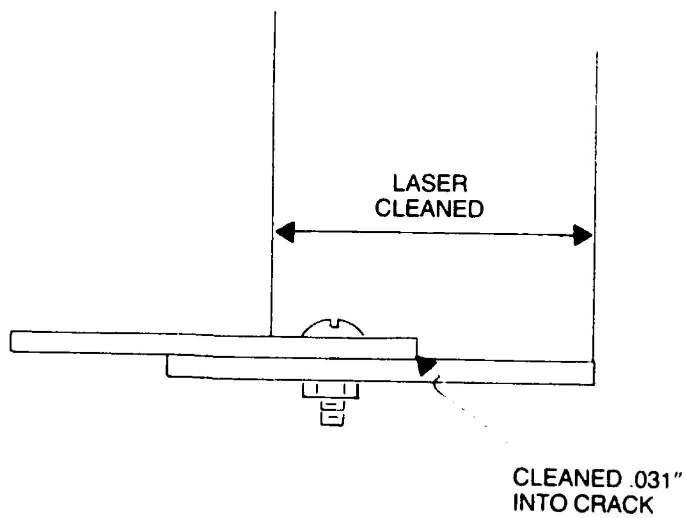



**Figure 27. Joint Cleaning Design**

### 23.2 Testing Results

Samples were collected by wiping surfaces during depainting of sample pieces. Filtration product from laser destruction of both paint and primer was collected and analyzed. No evidence of carbon formation could be detected.

The solid residue from laser depainting which appears to be predominately pigment shows a tendency to settle out in the immediate vicinity of the laser depainting operation. Air flow rates to insure removal to a filter were achieved with a simple blower system. Liners placed in the blower collection tube showed no evidence of collection of material which might adhere to the tube walls.

#### 23.2B Seam cleaning and corrosion test results.

Twelve samples were laser depainted with laser penetration into the seam approximately 1/32 inch. All samples reprimed and repainted and subjected to 720 hour salt spray corrosion resistance test.

All samples showed slight to moderate blistering but no seam corrosion. These corrosion results were equal to or better than the corrosion results obtained under the same conditions with no seam present. See Figure 28.

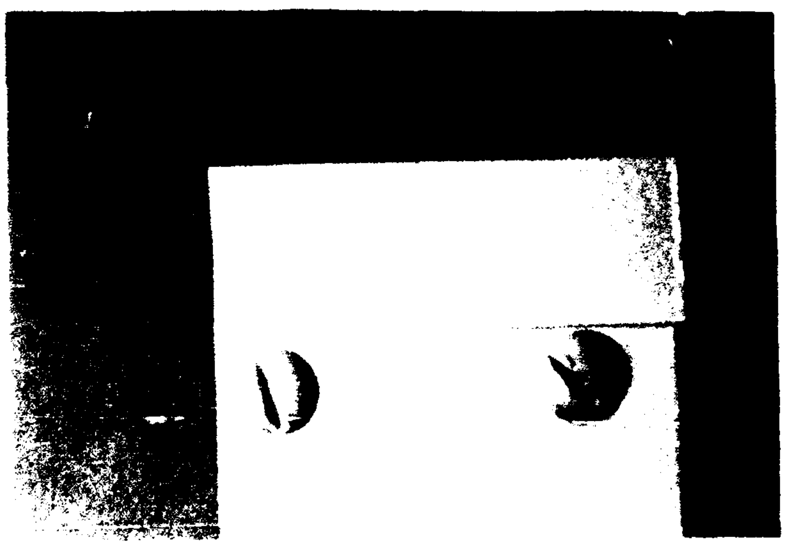


**Figure 28. Repainted joint after corrosion test**

### 23.3 Conclusions

Chemical analytical methods showed no evidence of residual carbon.

Indirect testing for the presence of carbon through corrosion testing of seamed samples showed no evidence of carbon induced corrosion. Carbon and soot like residues are produced with low fluence laser energy. All of the depainting done for this study was conducted in the more practical operating range of at least 8-10 joules per sqcm. At such fluence a clean reaction occurs with no evidence of carbon deposits even in cracks.

# 24.0 COMPLETE SYSTEM

## 24.1 Analysis of Complete System

The investigators analyzed and outlined a laser paint stripping system. The analysis of such a system includes data on possible vision, control, safety, and environmental protection devices to be used. The proposed system has the ability to remove paint from a substratum, leave the primer intact, and not be harmful to the substratum.

## 24.2 Testing Results

System Drawings A1, A2 and A3 are to be found in the Appendix.

## 24.3 Conclusions

A complete environmentally sound, economic system for the cleaning of aircraft was designed based upon the data derived during this study.

Since a portion of the incident energy is retained by the workpiece, particularly with anodized aluminum and with composites, it is important that a depainting system not dwell for long periods on the cleaned surface. The data produced under this contract suggest that damage to the substratum can be relatively easily avoided by system design to preclude exposure of any given surface to laser pulse frequencies of greater than 10 pulses per second or sustained pulses on a single location of greater than 50-100 pulses at higher frequencies. In the case of composite structures the limit for exposure can be set as that required to leave the primer in place.

In all cases some mechanism must be established to insure that the depainting laser energy not dwell for periods in excess of one quarter second on previously cleaned surfaces.

## 25.0 APPLICATION OF RESULTS

The results of this extensive study of the effects of the pulsed laser system on aircraft materials has successfully opened the potential for many applications of pulsed laser cleaning within the aircraft and aerospace markets as well as other totally unrelated markets. The validation of the benign nature of the process obtained through this study has enabled other industry segments to look at pulsed lasers as truly a viable new solution to very old and persistent problems, such as lead based paint removal, containment and disposal. This section will describe in general some of the possible uses for this revolutionary new technology.

### Aircraft Stripping

Possible applications for a pulsed laser stripping system abound throughout the aircraft and aerospace marketplace. Obvious applications are as straightforward as paint stripping of airframes, ranging from the smallest high performance jet aircraft to the largest jumbo aircraft employed by either the armed forces or the commercial airline fleets. The various aluminum skin thickness of these aircraft offer no problems to the laser energy emitted by a pulsed laser stripping system. Surface integrity of aluminum is in no way jeopardized by this efficient paint stripping method.

Paint from surfaces of composite components will also be readily stripped by a pulsed laser stripping system so long as proper procedures are followed to avoid risk of damage to the underlying organic substratum. In the case of stripping of composites, the paint system would be selectively removed down to the primer layer and that would be left intact. By so doing the composite substratum would assuredly be undamaged and ready for repainting.

### Related Aircraft Applications

Many other aircraft related applications are readily possible, including the stripping of the ground support equipment and various other support equipment used in this business. Many possible uses lie in the manufacturing arena of aircraft assembly and preparation of the various subassemblies and components that are required in the manufacture of an aircraft.

### Composite Stripping

Stripping of paint from composite structures is one of the most visible and difficult areas to master using any form of existing technology. The a pulsed laser stripping system may be one of the first technologies that lends itself well to this demanding task. Specific engineering details are now being defined to enable safe and efficient paint stripping of these surfaces.

Nose cones and radar domes of various sizes and shapes as well as

other composite components can readily be fixtured and stripped. Hand held and automation assisted stripping of composite airframes in a similar manner to that of aluminum skinned frames is being investigated and developed.

**Hand Operated or Robot Controlled**

A pulsed laser stripping system has been designed such that it can be hand operated on most substratum, such as aluminum, steel and other inorganic surfaces. The system is operated in a manner similar to existing hand held stripping methods, giving the operator control of the stripping process and allowing visual inspection of the results. The studies done indicate that the human factors are important to the cleaning process and should not be eliminated from the control and operation of a stripping system.

The future integration and interfacing of a pulsed laser stripping system to a robot is simply an engineering task to be undertaken with an appropriate automation supplier. Robot automation companies have indicated much interest in working with laser companies to couple a pulsed laser stripping system to their robots or other automation systems.

Composite stripping will initially most likely require some form of automation or fixturing. Currently various beam control strategies are being investigated such as would provide adequate control of the laser energy to enable full hand operation of a pulsed laser stripping system on all surfaces, including composites and even paper faced dry wall for residential lead based paint removal.

**The Clean Way To Clean**

One of the main advantages of a pulsed laser stripping system is the cleanliness it exhibits as it strips the surface of a coating. No usage of raw materials in the stripping process means no contamination or collection of such media. Contamination by stripping media of the surrounding work area as well as the piece of equipment being stripped is of significance, especially if the contaminating material could possibly cause related shutdowns or premature failures of electronics, motor bearings or other sensitive components. A well designed pulsed laser stripping system can continuously collect its residue as it strips the surface and safely contain it in industrial grade filters for ease of disposal.

Even more important is a long term benefit provided by a pulsed laser stripping system. This benefit results from the fact that the laser energy actually converts the organic portions of the paints and primers back into simple non-toxic gases and does not require that they be added into the waste stream. Waste disposal is becoming more and more controversial and expensive in all of the traditional surface stripping industries. With pulsed laser stripping the only residue to be disposed of is the actual volume

of the remaining inorganics, namely the pigments and any heavy metals that may be present within the paint and primer systems being removed.

This may not seem too significant, but an example of the actual savings is seen through the simple comparison found in waste streams generated in the stripping of a single F-4 fighter. Plastic bead blasting generates approximately 1500 pounds of waste. Chemical solvent stripping generates approximately 2000 pounds of waste. Pulsed laser stripping would generate only approximately 20 pounds, which is less than the weight and volume of the original surface coating when applied. The obvious long term benefit of this new technology for lengthening the life span of landfills and reducing the toxicity of the waste is evident.

Society as a whole is being asked to do everything possible to reduce the amount of waste generated, industry of all types should take whatever steps they can to do their part. A pulsed laser stripping system is a new technology which is becoming available to significantly reduce the wastes generated within many segments of industry.

**Hazardous Coating Removal**

A major area of interest for a pulsed laser stripping system is in the removal and containment during removal of lead based paints and other potentially harmful and toxic coating systems such as tri-butyl tin, an antifoulant coating. A pulsed laser stripping system removes the coating and converts any toxic organic components into non-toxic products. The inorganic components of the coating are converted into particulate metal oxides which are easily collected and contained through a vacuum filtration system.

The gaseous emissions appear to be predominately carbon dioxide and water with traces of other by-products. A National Science Foundation grant is currently supporting the necessary detailed analysis of off gas from a large system. It is expected that the gaseous emissions from a pulsed laser stripping system will prove to be substantially less than those of the average family automobile.

The ability of a pulsed laser stripping system to safely and efficiently remove lead based paints and primers, opens many opportunities within various outdoor steel structure stripping applications. Shipyard utilization on various marine coatings, such as tri-butyl tin, offer many advantages and possible uses throughout the shipyard from initial construction to total refurbishing activities.

With ever tightening regulations and growing public awareness of the harmful effects and vast disposal problems of existing abrasive blasting technologies, a pulsed laser stripping system is a welcome introduction, optimistically awaited by industry and regulatory agencies alike.

**Broad Market Potential**

System producers are investigating and receiving much interest from other target industries including; complex steel structure coating removal including highway and railroad bridges, Army Corps of Engineers structures such as locks and dams, water towers and tank farms, off shore oil and gas platforms, and many applications within shipyards. Manufacturing applications, fine art restoration, rubber removal from airport runways and from automotive tire molds are a few other viable uses for a pulsed laser stripping system. As such systems continue to penetrate various market sectors new forms of use and new applications will continue to be developed.

## APPENDIX

### A LASER PAINT STRIPPING SYSTEM - NOMENCLATURE

A laser paint stripping system can be either a truck-mounted or a track-mounted unit as shown in the attached conceptual illustration. (Figure A-1) The laser will be equipped with a beam pipe and an arm that provides access to all portions of the aircraft. The end of the arm will be equipped with an operating head incorporating a beam wobbler, a window or camara for visual control, and a fume collection device.

The various components are further presented in block diagram form. (Figure A-2) The individual blocks represent the following components of the complete system.

LASER
- 2 KW pulsed $CO_2$ laser.
- Output variable from 100 watt to 2 KW.
- Pulse width variable from 8-30 microseconds.
- Pulse rate variable from single shot to 200 pps.
- Packaged to withstand harsh industrial environment and rugged enough to be moved easily to and at job sites.

COLLIMATOR
- A lens system for adjustment of the beam to the proper size and divergence to fit through the beam pipe and arm.

BEAM PIPE
- Pipe which encloses the beam between structurally anchored fixed beam benders used in situations where the laser and the delivery arm are not contiguous.

BEAM BENDER
- Diamond turned copper mirror, heat sunk to its enclosure, used to change direction of the beam where no motion is required.

DELIVERY ARM
- A series of 2 inch to 8 ft beam pipes and 360 degree swiveled beam benders which permit either manual or automated movement of the beam to all parts of the aircraft.

BEAM WOBBLER
- A single or two axis wobbled mirror system (Figure A-3) which changes aim point for the beam between pulses such as to give a line of minimally overlapped pulses up to 15 cm long or a square pattern of pulses up to 15 cm square. The system is of such focal length as to give a 1-2 inch depth of field at the

work piece with fluence of 8-15 joules per sqcm.

BEAM PROXIMITY DETECTOR

- A probe to maintain controlled distance from the wobbler mirror to the work piece. The probe defined distance to the workpiece is varied by the controller with changes in laser output so as to maintain a constant fluence on the workpiece.

FUME COLLECTION HOOD

- A hood in which are mounted the beam wobbler and the beam proximity detector as well as a window for monitoring cleaning progress. In a fully automated version the window would be displaced by a vision system coupled with the controller.
- The hood will also be equipped with air inlet and flow direction vanes to insure uniform flow of air across the area of the workpiece being cleaned.

EXHAUST AND FILTRATION SYSTEM

- A 200-500 cuft per minute exhaust fan will pull all spent gases through a filter bag house equipped with industrial grade filters for collection of all pigment residues. One to two micron filters are adequate to collect all particulate material.
- The fan exhaust will be vented to the atmosphere.

CONTROLLER

- Monitor for all safety interlocks.
- Controls all operation of the laser.
- Provides system diagnostics.
- Controls both laser and beam wobbler to give uniform energy distribution.
- Monitors air flow and exhaust rates.
- Feeds back to beam proximity detector to insure correct laser fluence on the workpiece.
- Provides an interface with any overall automation which may be desired.

OPERATOR INTERFACE

- Contains all manual controls and both laser and system performance indicators.

**OPERATIONAL FACTORS**

A pulsed laser stripping system can be engineered and designed to efficiently operate on normal power generating supplies. Full production systems of 2KW power output will most likely require input power of 440 volt, 100 amp 3 phase power. Common gas powered generators can easily provide sufficient power capacities for applications requiring field power generation.

For the following example, power usage requirements and other specifications are presented for an existing 200 watt average power demonstration system and estimated for a 2KW system.

Input power: 50 amp 220 volt (200 watt system)
100 amp 440 volt (2KW system)

Output power: ~200 watts average power through the arm.
~2KW watts average power through the arm.

Spot size of beam: ~0.15 sq.cm. (200 watt system)
~1.5 sq.cm. (2KW system)

Effective footprint (with wobbler):
0.15x2.0 cm.(200 watt system)
1.5x20 cm. (2KW system)

Pulse frequency: variable from 1-250 Hz.

Pulse width: variable from 12-30 microseconds.

Optimum fluence: 8-15 joules/sqcm/pulse.

NOTE: Fluence is variable with the distance from the wobbler to the work surface. Moving closer to the work surface gives a smaller effective footprint and a higher fluence and the opposite is true as the wobbler is moved further from the work surface. Depending on the substratum being stripped the operator can determine the most practical and efficient operating fluence and standoff distance.

The power efficiency presented in this example represents wall plug efficiency for the total system including vaccum, oil, and filter pumps plus all controls and other associated equipment.

A pulsed laser stripping system being a $CO_2$ laser emits light energy in the far infrared spectrum at 10.6 microns. This has advantages when it comes to safety since this wave length of light does not penetrate glass or plastic and consequently common safety glass material is an adequate safety barrier. This wave length has also proven to couple extremely well with the organic constituents of the paints and primers used for coating surfaces. This allows for efficient and practical use of a pulsed laser stripping systemon virtually any surface coated with any type of paint system.

Paint stripping rates will vary with the type and thickness of the actual paint system. Systems can be rated for performance in terms of approximate stripping rates of square feet per hour per mil of paint thickness. This establishes a common ground for comparisons since actual surface coatings are never completely uniform in thickness across the whole surface.

A full power (2KW) system should be able to effectively remove paint coatings at a rate of approximately 600 square feet per hour per mil of paint. Any actual paint system may influence

this removal rate in either a positive or negative direction. The achieved stripping rates in any practical application of the equipment will also be influenced by the configuration of the object being cleaned and the lost time encountered in gaining access to the various work surfaces.

**LASER NUMBERS DISCUSSION**

The various measures of laser energy and power are frequently difficult to understand as they relate to one another. Lasers are commonly referred to by average power output, i.e. 200 watt or 2KW. A 2KW laser would require power input of 10-20 KW to get the 2KW laser beam output. The 2KW output represents 2,000 joules(watt seconds) and such a machine would put out 2,000 Joules. If the energy level of this machine design is 10 joules per pulse then a pulse rate of 200 hertz would be required to achieve the 2,000 joule output. The per pulse energy of lasers tends to be fixed by basic design factors and variation of power output is achieved by variation of pulse frequency. This example machine would have only 1KW output if operated at 100hz.

With the laser output being fixed as to energy per pulse, any variation of energy on a work piece is achieved by variation of spot size which is achieved by variation of distance to the work piece in a focused beam. The above example of a 2KW laser operating at 200 hz would produce a 10 J pulse and a 1 cm square spot could be covered by each pulse with a fluence of 10 J/sqcm. If the spot size was decreased to 0.5 cm square the fluence would increase to 40 J/sqcm.

Another independent number is that of pulse duration. The pulse width or duration of a pulsed laser stripping system equipment can be varied from 12 to 30 microseconds. Such variation will not change the output energy per pulse or the average power of the laser. This variation will to some extent influence the efficiency of paint removal by the laser system depending on the nature of the paint. In any practical operating case optimum paint removal rates can be achieved by control of a combination of fluence and pulse width.

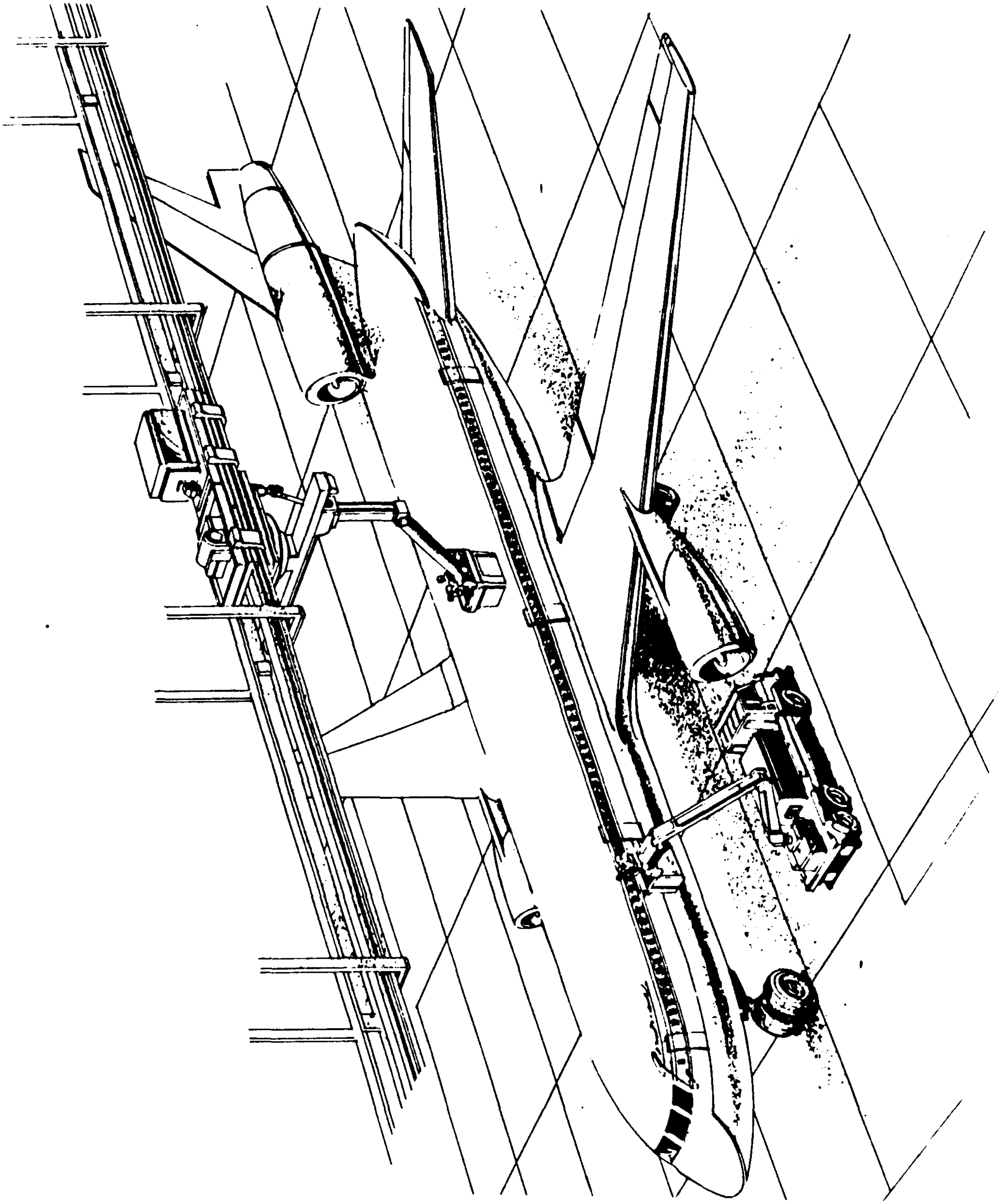


**Figure A-1**
**Aircraft Cleaning**

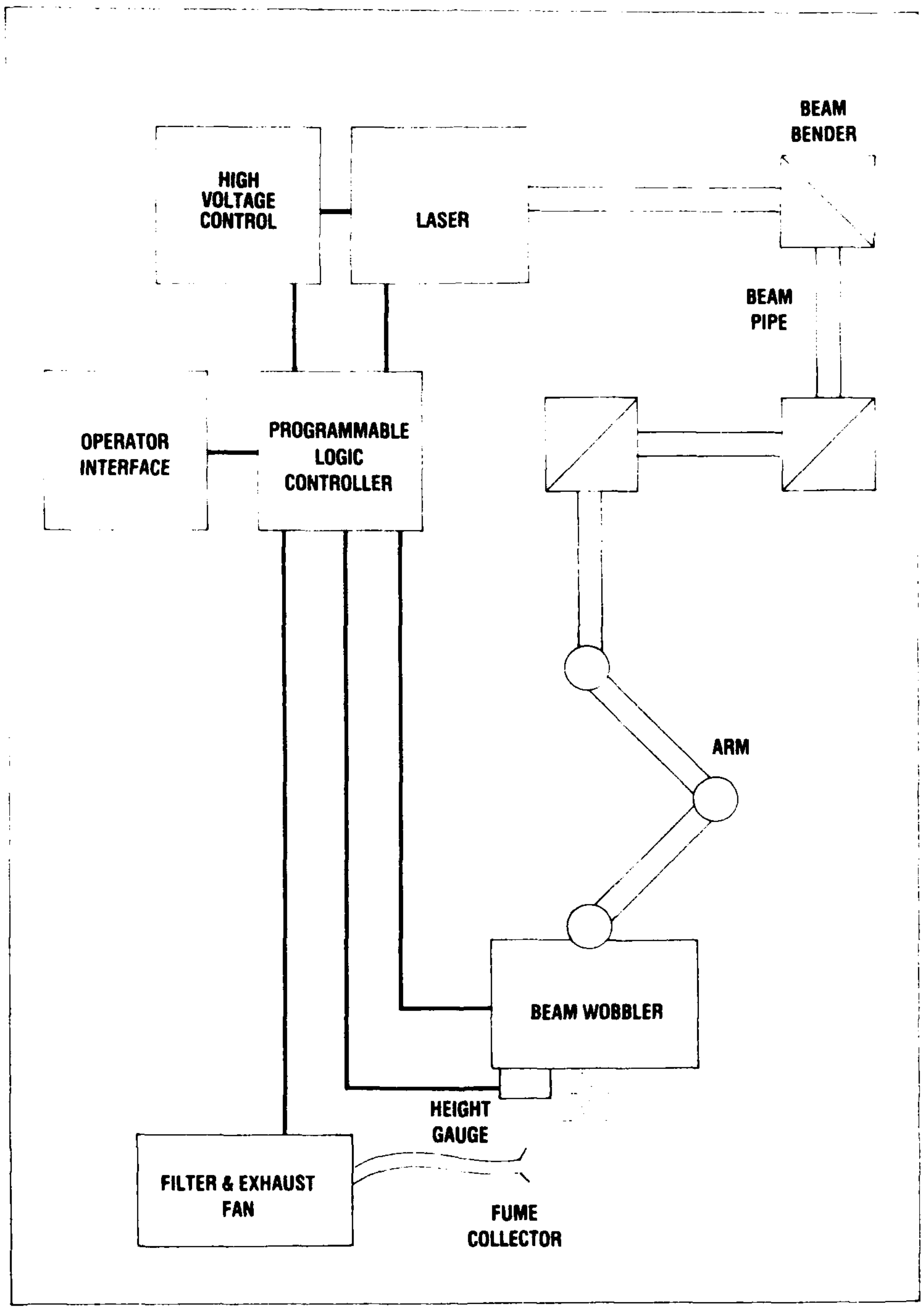



**Figure A-2**
**Depainting System Outline**

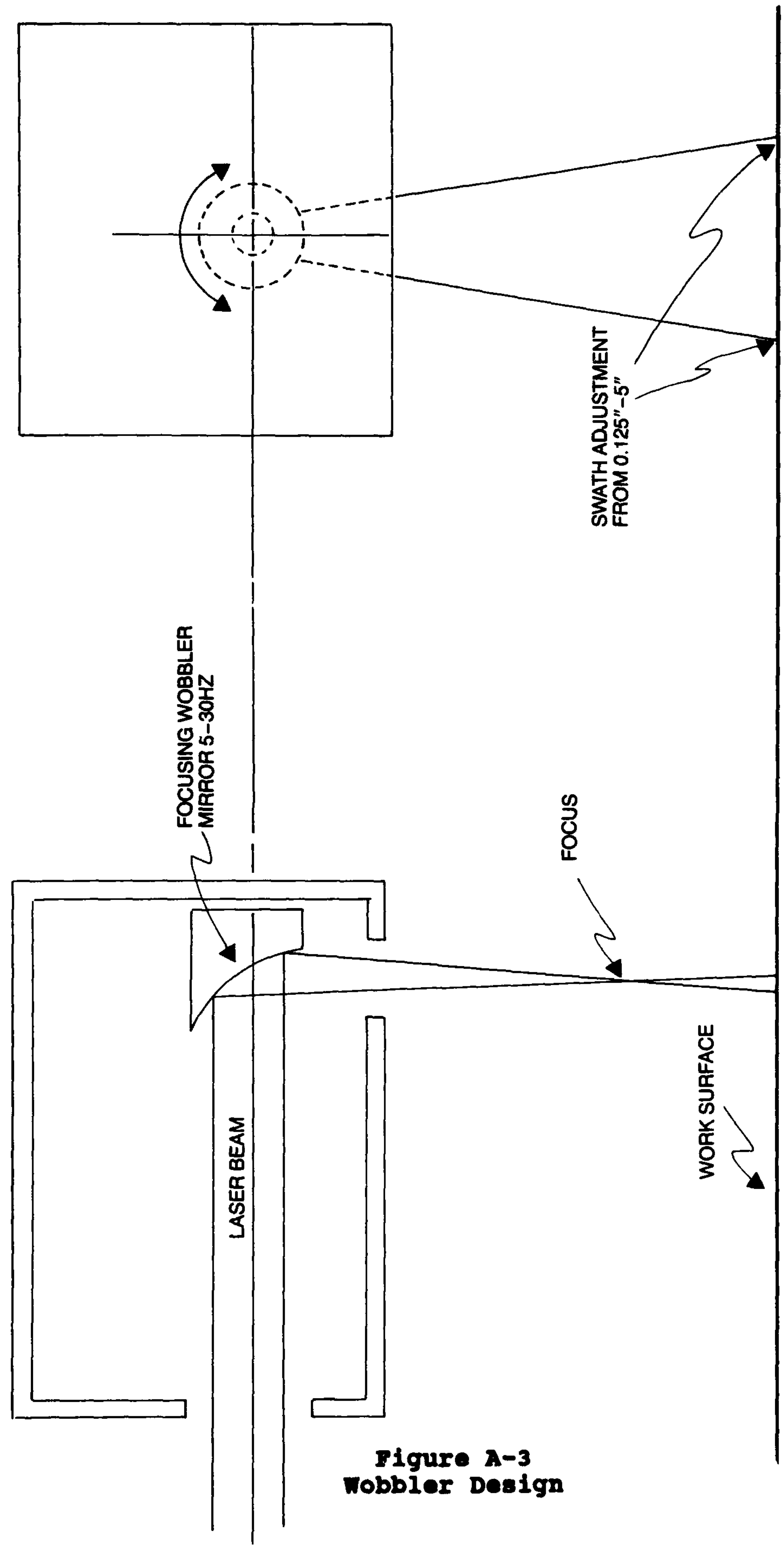



**Figure A-3**
**Wobbler Design**



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